Impact-Echo Instruments, LLC
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Impact-Echo User's Manual

A Self-Teaching Course and Reference for the Impact-Echo Method and Software

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The impact-echo test instruments and software
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Table of Contents

Section I: The Impact-Echo Method

The Impact-Echo Method

Impact-echo is a method for nondestructive testing of concrete and masonry structures, based on the use of impact-generated stress (sound) waves that propagate through concrete and masonry and are reflected by internal flaws and external surfaces. It can be used to determine the location and extent of flaws such as cracks, delaminations, voids, honeycombing, and debonding in plain, reinforced, and post-tensioned concrete structures, including plates (slabs, pavements, walls, decks), layered plates (including concrete with asphalt overlays), columns and beams (round, square, rectangular and many I and T cross-sections), and hollow cylinders (pipes, tunnels, mine shaft liners, tanks). The method can be used to locate voids in the grouted tendon ducts of many (but not all) types of post-tensioned structures. It can provide thickness measurements of concrete slabs with an accuracy better than three percent, and it can locate voids in the subgrade directly beneath slabs and pavements. When properly used the impact-echo method has achieved unparalleled success in locating flaws and measuring thickness in highway pavements, bridges, buildings, tunnels, dams, piers, sea walls, and many other types of structures.

An ASTM Standard Practice, C-1383-98a, entitled, "Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method" was first published in October 1998 and updated in April 1999. A copy is included as Appendix **B** in this manual.

Impact-echo is not a "black-box" system that can perform blind tests on concrete and masonry structures and always tell what is inside. The method is used most successfully to identify and quantify suspected problems within a structure, in quality control applications, such as measuring the thickness of concrete slabs, and in preventive maintenance programs, such as routine evaluation of bridge decks to detect delaminations. In all of these situations, impact-echo testing has a focused objective, such as locating cracks, voids or delaminations, measuring thickness, or checking a post-tensioned structure for voids in the grouted tendon ducts. Successful field work requires both an understanding of the impact-echo method and knowledge about the structure being tested.

Using This Manual and ImpactDemo Software

This manual, together with the software program **ImpactDemo** with its accompanying files of impact-echo test data, provide a comprehensive introduction to the impact-echo method for nondestructive evaluation of concrete and masonry. It also introduces the software, **Impact-E**, used with Impact-Echo test systems made by Impact-Echo Instruments, LLC. **ImpactDemo** is a live, active version of the software, with all the capabilities of **Impact-E** except real testing, which is simulated. Both **Impact-E** and **ImpactDemo** have extensive on-line Help Systems.

ImpactDemo software is Windows based. It must be installed on a computer with a Microsoft Windows 95, or later (e.g. Windows 98 or Windows 2000), operating system. (Instructions for installing the software are in the next section.) Users must have at least an elementary knowledge of the Windows operating system. The user can interact with the software through a mouse or keyboard. Throughout this manual it is assumed that a mouse is being used. The instruction "click **X**" instructs the user to place the mouse pointer on object "**X**" and press the left mouse key. Alternative instructions for using the keyboard are shown in brackets, as in [Keyboard: press "**Alt+O**"].

This manual and the **ImpactDemo** software program have been designed to be used together. The manual is divided into sections, containing explanatory text and numbered action steps to be performed using the software. When the software program is installed, a data file of impact-echo tests on real structures is loaded into the computer memory, and used to explain how tests are performed and how the results are interpreted. ***Follow the action steps in sequence to obtain a comprehensive introduction to the impact-echo method and the software.*** Study each section until the methods and principles it covers are thoroughly understood before proceeding to the next section.

The Impact-Echo Book

Detailed information about the physics and mathematics of the impact-echo method can be found in the book, ***Impact-Echo: Nondestructive Evaluation of Concrete and Masonry***, by Mary J. Sansalone and William B. Streett, 1997, Bullbrier Press, Ithaca, NY. (Address inquiries to Bullbrier Press, R.R. 1, Box 332, Jersey Shore, PA 17740, telephone and FAX: 570-769-7345.) A copy of the book is included with each impact-echo instrument. It is a useful companion to this manual and **ImpactDemo** software. Elsewhere in this manual the book is referred to as *Sansalone and Streett*.

How Impact-Echo Works

Impact-echo is based on the use of transient stress waves generated by elastic impact. A diagram of the method is shown in Figure I-1. A short-duration mechanical impact, produced by tapping a small steel sphere against a concrete or masonry surface, generates low-frequency (70 kHz or less) stress waves that propagate into the structure and are reflected by flaws and/or external surfaces. Surface displacements caused by the arrival of reflected waves at the impact surface are recorded by a transducer, which produces an analog signal of voltage vs. time, called a waveform. This signal describes transient local vibrations, caused by multiple reflections of stress waves within the structure. The dominant frequencies in these vibrations are related to the depths from which stress waves are reflected within the structure. The analog signals are digitized by an analog/digital data acquisition system and transferred to the memory of a computer. Through a mathematical operation the voltage-time signal is transformed into an amplitude-frequency graph (a spectrum). Peaks in the spectrum identify the dominant frequencies in the waveform, which are used to calculate thickness and/or the depths of flaws. (*Sansalone and Streett*, Chapter 4, pp. 47-52.)

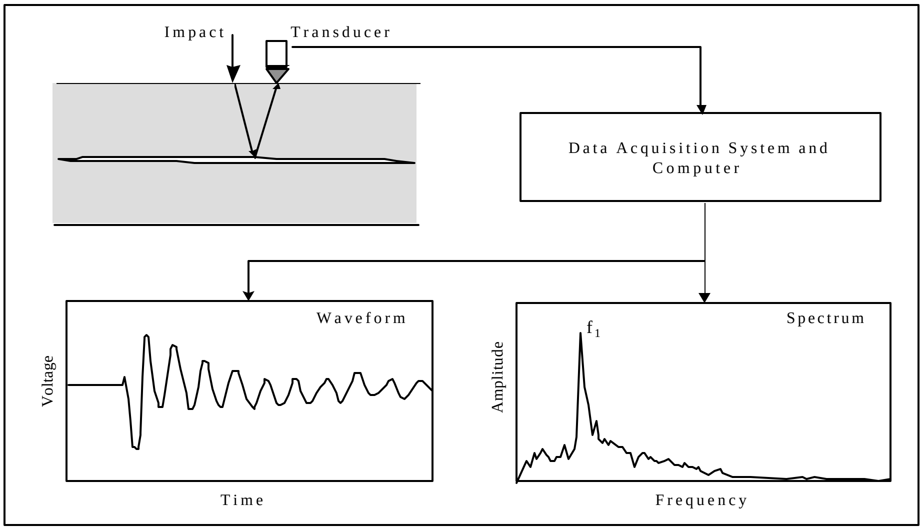

Figure I-1. Schematic diagram of the impact-echo method.

The patterns present in the waveforms, and the dominant frequencies identified by the spectra, provide information about the depth of flaws, or the dimensions of the structure such as the thickness of a pavement. For each of the common geometrical forms encountered in concrete structures (plates; circular and rectangular columns; rectangular, I-, and T-beams; hollow cylinders; etc.), impact-echo tests on a solid structure produce distinctive waveforms and spectra, in which the dominant patterns—especially the number and distribution of peaks in the spectra—are easily recognized. For solid structures the frequencies of the dominant peaks provide information about the thickness of the structure. If flaws are present (cracks, voids, delaminations, etc.) a different set of key frequencies is recorded, providing qualitative and quantitative information about the existence and location of the flaws.

Stress Waves

Two types of elastic waves propagate within solids: (1) dilatational waves, called primary waves or P-waves, and (2) distortional waves, called secondary waves or S-waves. A third type of elastic waves, known as Rayleigh waves or R-waves, propagates along the surface of a solid. The impact-echo method is based mainly on the effects produced by P-waves and R-waves. (See *Sansalone and Streett*, Chapter 3, pp. 29-46.)

Impact-Echo Field Test System

Figure I-2 is a photograph of a typical impact-echo field test system. It has five main components:

- A hand-held transducer unit (cylindrical unit on the left) that produces a voltage signal in response to surface

Figure I-2. A typical impact-echo test system.

displacements caused by reflected stress waves.

- A set of small, hardened steel spheres (in front of computer), called impactors, for producing impact-generated stress waves.
- A high-speed, analog-to-digital data acquisition system (left of computer) that receives and digitizes the signal from the transducer and transfers it to the computer memory.
- A notebook computer that receives, stores and processes the digitized signal from the data acquisition system, and displays the results in numerical and graphical form.
- A software program (**Impact-E**) that monitors and controls each test, and processes the data to produce output displays that provide information about the structure being tested.

With a seven pound notebook computer the system weighs about 13 pounds (6 kg) and can operate on its own internal batteries for 2 - 3 hours, or longer if extra notebook computer batteries are available. A 12 volt DC source, such as a car or truck battery, can be used to power the system and/or recharge the batteries.

Storage and Retrieval of Test Data

When impact-echo tests are performed with the field test system, test results can be saved to a file in the computer for later examination and analysis, and for printing copies of test results. The results of a single test are stored as a unique record in a random access file. The file can be on the hard disk or on a floppy disk or another storage device connected the computer.

Section II: Setup and Preparation for Testing

Getting Started With ImpactDemo

To set up a real impact-echo test system, cables are connected between the data acquisition system, the transducer unit, and the computer. The instrument can be powered by internal batteries, or by an external source (12v DC, or 220/110v AC). The data acquisition system and transducer unit are not needed when using the **ImpactDemo** software. Their actions are simulated by the software. If you have purchased an instrument with a computer, ImpactDemo is already installed.

Installing ImpactDemo Software

1. Insert Disk 1 in the appropriate drive (typically the **"a:"** drive) and select **Start** and **Run** in the lower left corner of the Windows screen [Keyboard: press the "Windows" key (not on all keyboards) and press "**R**"]. Enter **a:\setup** on the line labeled **Open** in the **Run** box that appears, and click **OK** [Keyboard: press **Enter**].

2. Follow the instructions on the screen. The software will be installed in a directory named **ImpactDemo**. The installation will create a program group called **Impact Echo** containing an icon for the **ImpactDemo** program (Figure II-1). The icon will also be installed on the computer's Desktop screen.

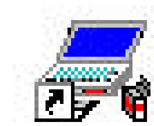

Figure II-1. The **ImpactDemo** icon.

Start the Program

3. Double-click the **ImpactDemo** icon on the Desktop screen, or on the **Windows** screen click **Start** and **Programs**. Click the **Impact Echo** group, and click **ImpactDemo** to start the program. [Keyboard: press the "**Windows**" key (not on all keyboards), press "**P**" to open the list of program groups, and use the up/down arrow keys to select **Impact Echo.** Press **Enter**, select **ImpactDemo**, and press **Enter** to start the program.]

When the program is started, the **Logo** screen (Figure II-2) appears for several seconds. The box at the bottom contains the Version Number of the software and its release date.

Figure II-2. The **Logo** screen.

After the **Logo** screen disappears, the **Main Menu** screen appears (Figure II-3). It consists of eleven command buttons, with captions that are largely self-explanatory. The actions produced by these command buttons are explained and illustrated in this and subsequent sections. When this screen first appears, 7 of the 11 command buttons are disabled (cannot be activated).

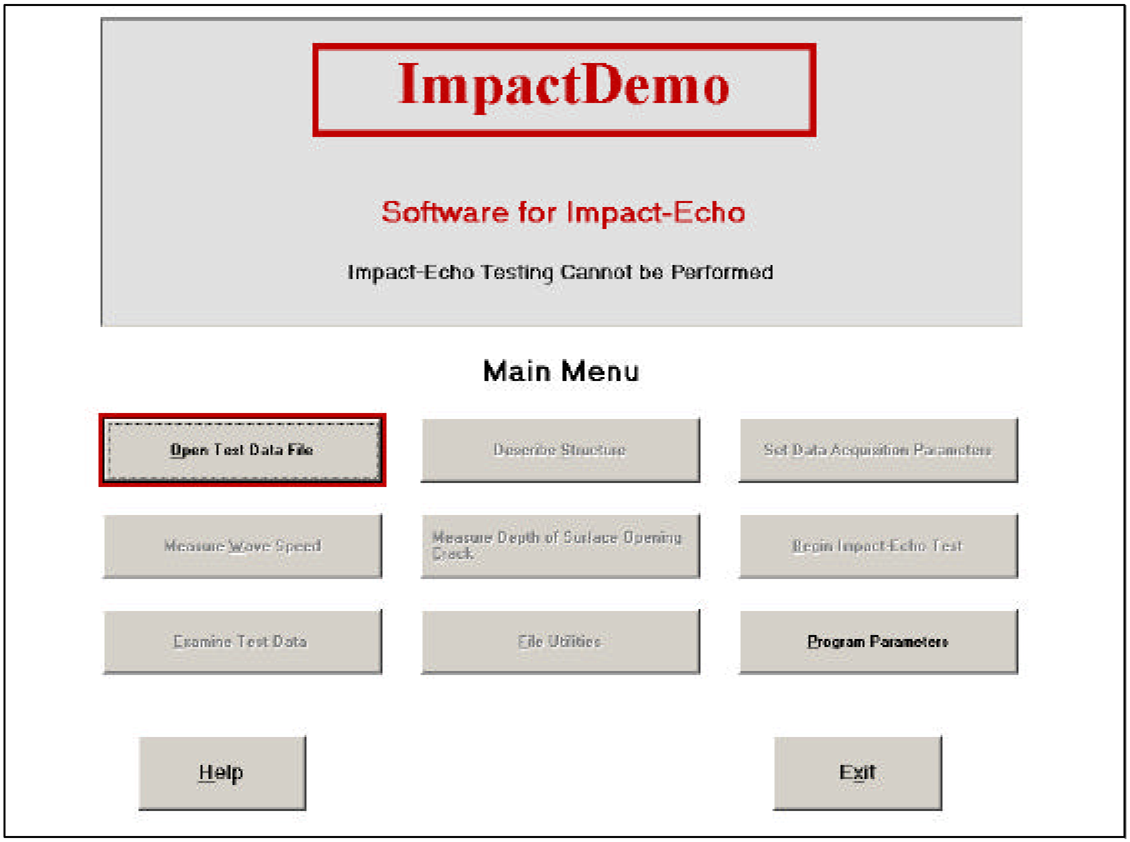

Figure II-3. The **Main Menu** screen.

4. Click **Help** [Keyboard: press "**Alt+H**"] to open the Help System. The Help System is in standard Windows format. Any topic can be accessed from any help screen. Most of the material in this manual is also covered in the internal Help System. The Help System is accessed through **"Help"** command buttons. Close the Help System by clicking "X" at the upper right of the **Impact-Echo** help screen.

Explore the "Program Parameters" Settings

5. Click the **Program Parameters** command button with the mouse. [Keyboard: press the "**Alt**" key plus the key of the underlined letter "**P**"[1] or press the **Enter** key when the **Program Parameters** button "has the focus", indicated by a red border. Use the **Tab** key to shift the focus from one object to another.] The **Program Parameters** selection box appears (Figure II-4).

6. Click the **Show screens in black and white** option and click **OK**. [Keyboard: press "**S**", then "**O**".] The **Main Menu** screen (and all other screens) appear with dark lines and letters on a white background. Click **Program Parameters** again and remove the check from the **Show screens in black and white** box to restore color.

7. The default unit for the display of dimensions is millimeters (mm). Click the **Show all dimensions in inches** checkbox to cause all dimensions to be displayed in inches. [Keyboard: press "**Alt+d**".]

8. If the **Screen for bad signals** box is checked, the software will automatically check the incoming waveform to determine if it has the basic characteristics of a valid impact-echo signal. If it does not, the computer will emit a loud "buzzer" signal, and the waveform will be plotted as a red line. These signals should be ignored. The screening system can be turned on and off using a command button on the testing screen.

9. The **Screen Size (pixels)** option is used to make the important screens in the program fill the entire screen on the computer being used. The default is **800x600** pixels.[2] For computers with a maximum **Desktop Area** of **640x480** pixels, choose this option.

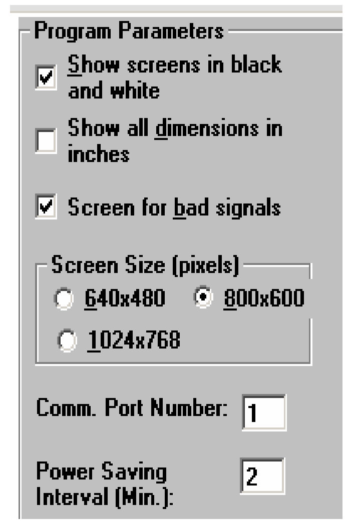

Figure II-4. The **Program Parameters** box.

10. The **Comm. Port Number** designates the communications port to be used by the data acquisition system. This setting is not used by **ImpactDemo**. It is used only during testing with **Impact-E** software system (see Instrument Manual, Par. 7).

11. The **Power Saving Interval (Min.)** is designed to conserve battery power in the data acquisition system. After a signal is received by the system it will automatically go into the Sleep Mode (reducing power consumption by 90%) if another signal is not received within the

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[1] Windows protocol provides that an underlined letter in the caption of a command button or other object can be used to activate or select that object by pressing the **Alt** key together with the key of the underlined letter.

[2] To check the screen size on your computer, go to the Windows screen, click **Start**, **Settings**, **Control Panel**, and double click on the **Display** icon. The screen size in pixels is the **Desktop Area**, found under the **Settings** tab. If possible, choose 800x600 as the **Desktop Area** for your computer.

specified interval. The default value is 2 minutes. To change this value, enter another integer in the text box and press **Return**. The new value is stored in a file when the system is shut down, and will be used again when it is restarted. Intervals between 2 and 5 minutes are recommended. This setting is not used by **ImpactDemo**. It is used only during testing with **Impact-E** software system (see Instrument Manual, Par. 8).

12. Click **OK** to return to the **Main Menu** screen.

Open A Data File

A new or existing test data file must be opened each time the program is started. The results of a single impact-echo test are stored as a record in a random access file. A data file is specified by a path designation, consisting of the drive identification (**c:** for hard drive, **a:** for floppy disk, etc.) followed by the directory name, subdirectory name (optional), and file name, separated by back slashes (\).

13. Click **Open Test Data File** on the **Main Menu** [Keyboard: press "**Alt+O**"]. The **Default File** screen appears (Figure II-5). The **Default File** screen prompts the user to open a file on the **c:** drive, in the directory named **ImpactDemo**, subdirectory **TestFiles**, with a file name consisting of the current date ("ddmmmyy") followed by the suffix ".dat". This creates files with names based on the dates on which the files are created. If a different file name is desired, it can be entered in the text box.

14. Click **OK** to open the file named in the text box.

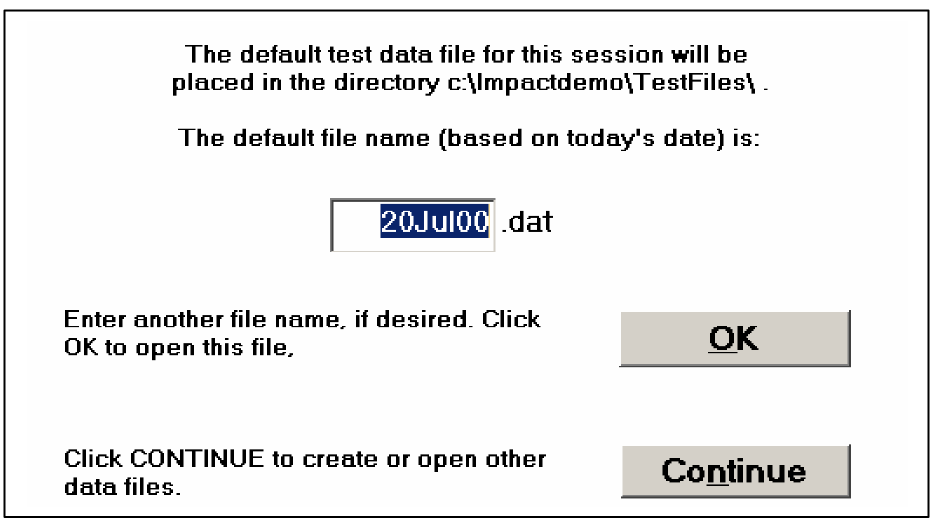


Fig. II-5. The **Default File** screen.

15. To open an existing file, or a new file in a different directory\subdirectory, click **Continue** to bring up the **Open Test Data File** screen (Figure II-6). A test data file named **c:\ImpactDemo\TestFile.dat**, containing impact-echo test results from projects

in the USA and elsewhere, is included with the **ImpactDemo** software program. When the software is installed, this file is installed in the **ImpactDemo** directory that is created on the **c:** drive (the hard disk) during the installation.[3]

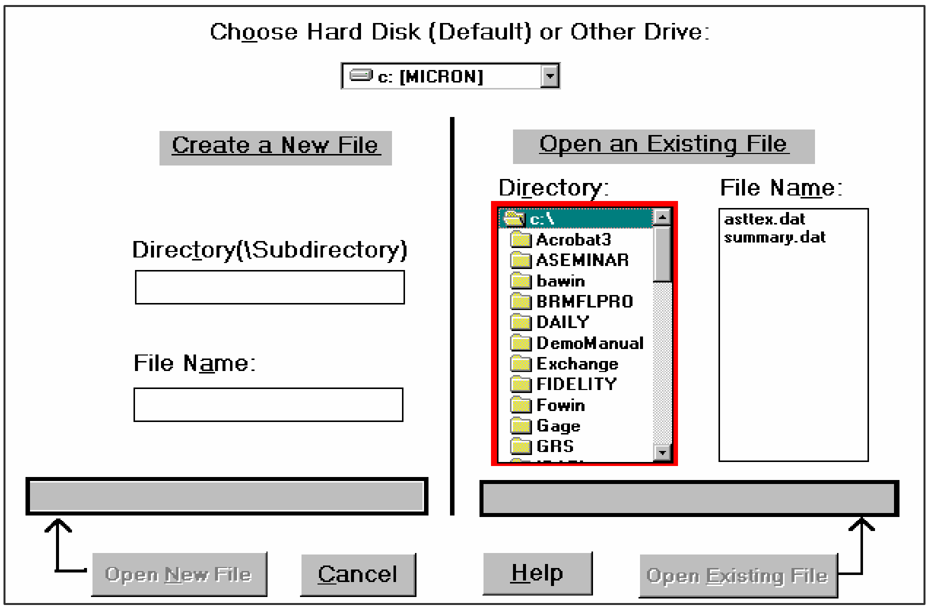
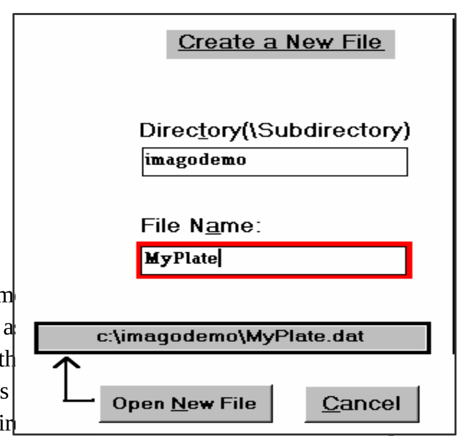


Figure II-6. The **Open Test Data File** screen.

Create a New Data File in a New or Existing Directory\Subdirectory

14. Choose the drive for a new file by clicking the drop down drive box at the top of the screen. [Keyboard: press "**Alt+o**" to select the drive box, followed by the letter of the desired drive ("**c**", "**a**", "**d**", etc.).] The **c:** drive (hard disk) is the default.

When the "Open Test Data File" screen is opened (Figure II-7) the **Open New File** and **Open Existing File** buttons are disabled. When the file to be opened has been identified, one of these buttons will be enabled. At this point a new data file will be opened in the **ImpactDemo** directory for impact-echo tests on a plate.



[3] The description of files in terms of paths, drives, directories and file nam filing system. For example, consider the storage of a test result a **c:\impactdemo\TestFile.dat**. Think of the computer as a file cabinet and th directory, **impactdemo**, as a folder in the drawer; the file, **TestFile.dat**, as numbered entry on the document. The drawer can hold multiple folders (dir documents (files), and each document can contain multiple entries (records). Subdirectories are folders within folders.

15. Click the **Direc<u>t</u>ory(\Subdirectory)** text box [Keyboard: press "**Alt+t**"], enter the directory name **ImpactDemo** in the box, and press **Enter**. (***<u>Always</u> press the Enter key to transfer information entered into a text box into the computer memory!)*** Enter the file name "MyPlate**"** in the **File N<u>a</u>me** box. The suffix **.dat** is added automatically and the complete file designation appears in the gray box below (figure II-6). Press **Enter** to enter the file name into memory.

16. Click **Open <u>N</u>ew File** [Keyboard: press "**Alt+N**"] to create and open the new file. A message box appears, stating that the file has been opened and that it contains no records. Click **OK** on the message box [Keyboard: press **Enter**] to close it. Control is returned to the **Main Menu** screen, and all command buttons are enabled (Figure II-8).

Figure II-7. The **New File** portion of the **Open Test Date File** screen.

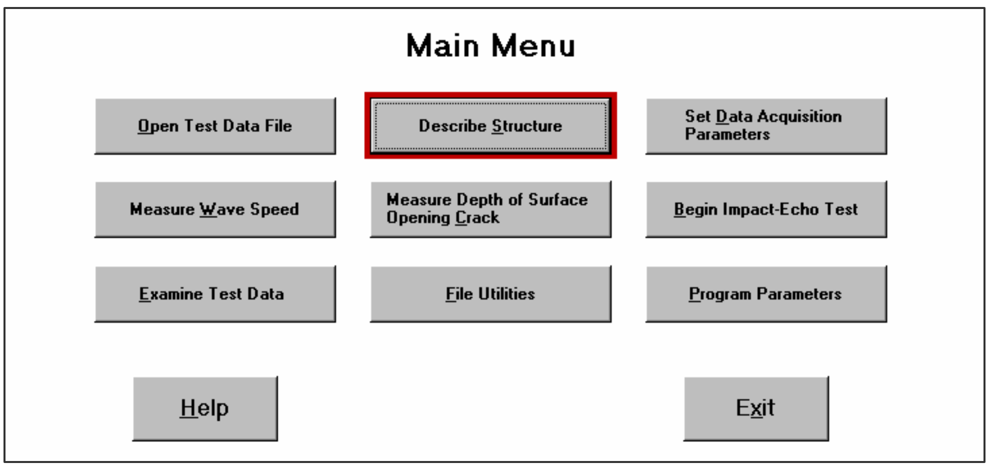


Figure II-8. The **Main Menu** screen with all command buttons enabled.

The next step in preparation for impact-echo testing is to describe the structure, by entering the structure name, characteristic dimensions and P-wave speeds. One or more of these quantities may have to be estimated. In this example, impact-echo tests are to be performed to determine the thickness of concrete plate. The thickness is unknown, but is thought to vary from about 300mm to 600mm. A starting estimate of 400mm will be used. The P-wave speed has been measured independently using two transducers held a fixed distance apart on the surface (the method is described later) and found to be 3996 m/s.

<u>Describe the Structure</u>

17. Click the **Describe <u>S</u>tructure** command button on the **Main Menu** screen. The **Choose Structure Type** option box appears (Figure II-9). A plate structure about 400mm thick is to be tested.

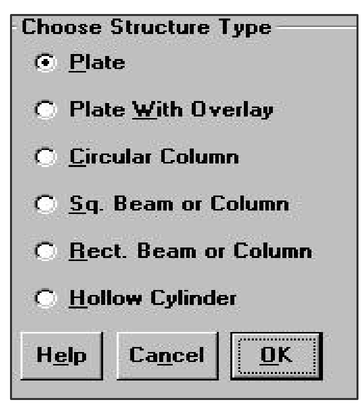


Figure II-9. The **Choose Structure Type** option box.

18. Select the **Plate** option, and click **OK.**[4] The **Plate** screen appears (Figure II-10).

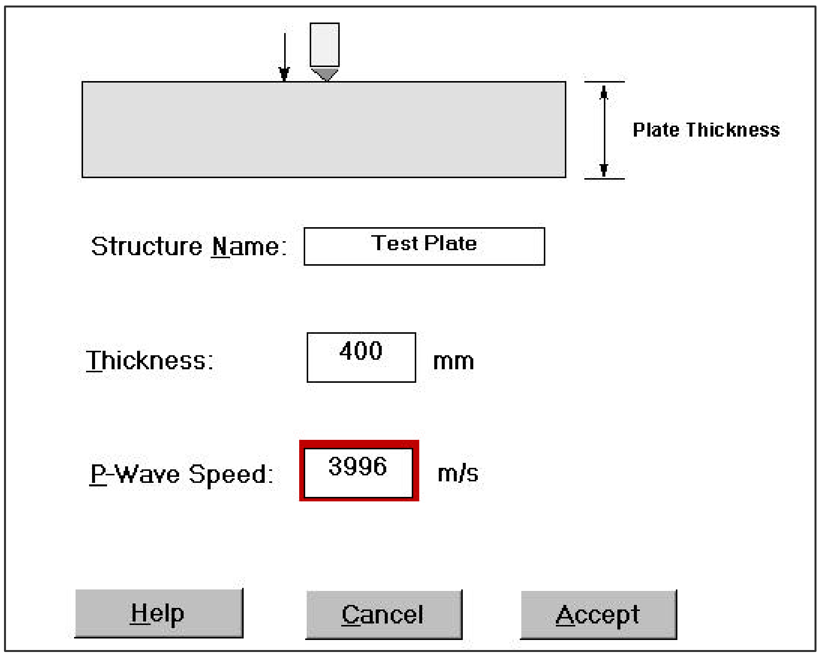


Figure II-10. The **Plate** screen.

19. Click on the **Structure Name** text box to select it [Keyboard: press "**Alt+N**"]. Enter **Test Plate** as the **Structure Name** and press **Enter**. Enter 400 for the **Thickness** (in mm) and 3996 for the **P-Wave Speed** (m/s), pressing the **Enter** key after each entry.

20. Click **Accept** on the **Plate** screen to return to the **Main Menu** screen (Fig. II-8).

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[4] For impact-echo purposes, a "plate" is defined as any structure with two parallel faces, for which the lateral dimensions are at least five times greater than the thickness.

Begin Impact-Echo Testing

21. On the **Main Menu** screen click **Begin Impact-Echo Test** [Keyboard: press "**Alt+B**"]. A message box appears with the message, "This is a demo version of Impact-E software. Testing cannot be performed." Click **OK** or press **Enter.** The **Begin Testing** screen appears (Figure II-11).

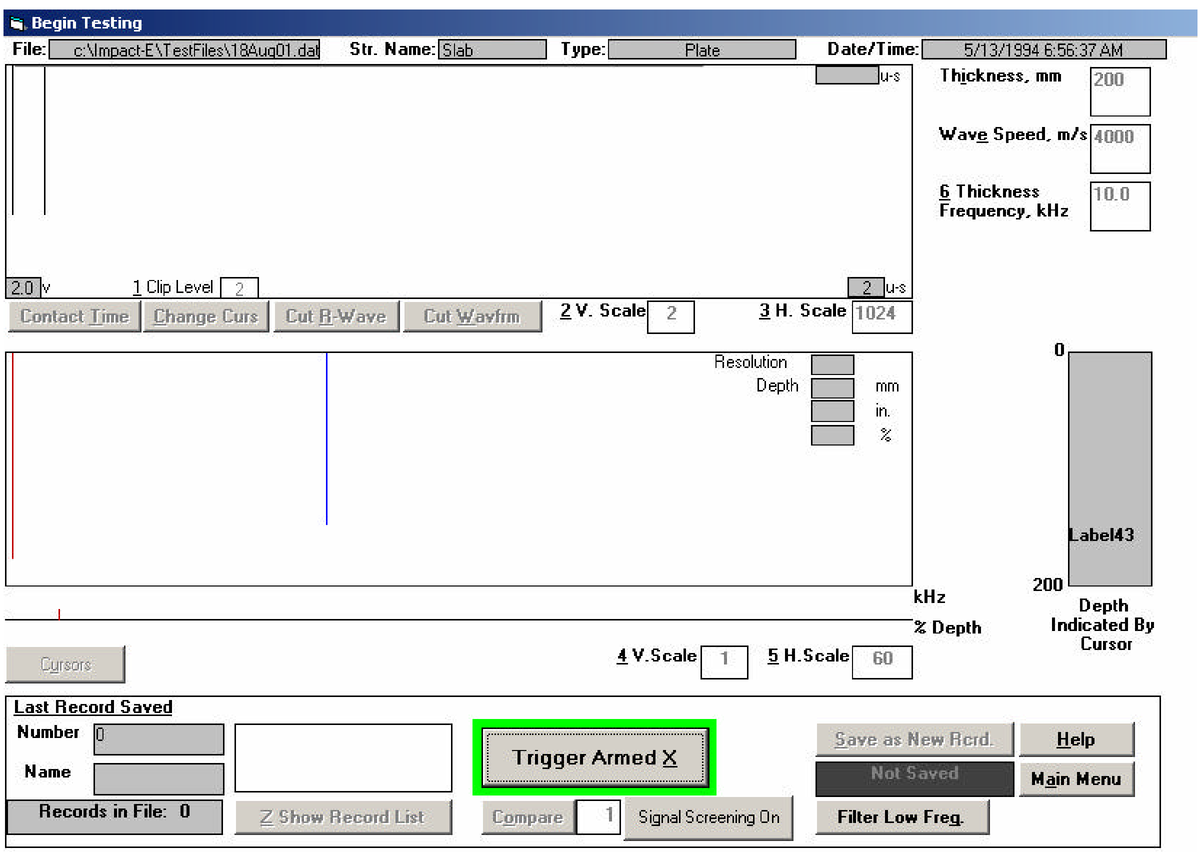

Figure II-11. The **Begin Testing** screen, opened after a new file has been created.

Figure II-11 shows the "Begin Testing" screen as it appears after a new file, or an existing file that contains no records, has been opened, and testing is ready to begin. The graphs for the waveform and spectrum—the two large rectangles on the screen—are blank (the vertical lines within these rectangles are markers and cursors that will be explained later). The large command button in the center of the lower part of the screen, with the caption **Trigger Armed X**, has green border that is flashing at intervals of about 0.5 seconds, indicating that the data acquisition system is armed and ready to receive a test signal. The Date/Time in the upper right corner of the screen is entered automatically when an impact is made, and stored as part of the test record.

Figure II-12. Close up of impact-echo test on a concrete floor.

At this point the transducer is placed in contact with the structure to be tested, and an impact is made (Figure II-12). The handle of the transducer is pressed down, and the impactor (a small steel sphere on the end of a spring rod) is then tapped lightly against the surface. The force of the impact is equivalent to dropping the sphere from a height of one or two meters. The diameter of the sphere, rather than the force of the impact, is the most important factor in determining the character and behavior of the resulting stress waves. The signal is only weakly dependent on the force of impact.

Figures II-13 and II-14 show tests being performed on a concrete beam, and on the wall of a ventilation shaft for a railway tunnel.

Figure II-13. Testing a concrete beam, football stadium, USA.

Figure II-14. Testing a concrete wall in a ventilation shaft for a railroad tunnel.

Within one or two seconds after the impact, the results appear on the computer screen: a waveform (the voltage-time signal from the transducer) in the upper graph and the amplitude spectrum (a plot of amplitude vs. frequency) in the lower graph. (A normal signal will be accompanied by a "bell" sound on the computer. If a loud "buzzer" sound is emitted, the signal is of questionable value and should be ignored.) The results of a test to determine the thickness of a plate are shown in Figure II-15, as they would appear on the screen immediately after the impact. To view this screen on your computer, perform the following steps:

22. On the **Begin Testing** screen, click **Main Menu** [Keyboard: press "**Alt+a**"] to return to the Main Menu screen,

23. Click **Open Test Data File** [Keyboard: press "**Alt+O**"],

24. Double click **ImpactDemo** directory in the **Directory** box [Keyboard: press "**Alt+r**", select **ImpactDemo** using the up/down arrow keys, and press **Enter**],

25. Double click on the file **TestFile.dat** in the **File Name** box [Keyboard: select **TestFile.dat** using up/down arrow keys, press **Enter**, and press **Enter** again] to open the file,

26. On the Main Menu screen, click **Begin Impact-Echo Test** [Keyboard: press "**Alt+B**"].

The screen shown in Figure II-15 will appear on your computer. This shows the results of a test on a concrete slab, as they would appear immediately after the test has been performed. The analysis and interpretation of test results will be discussed in later sections of this tutorial.

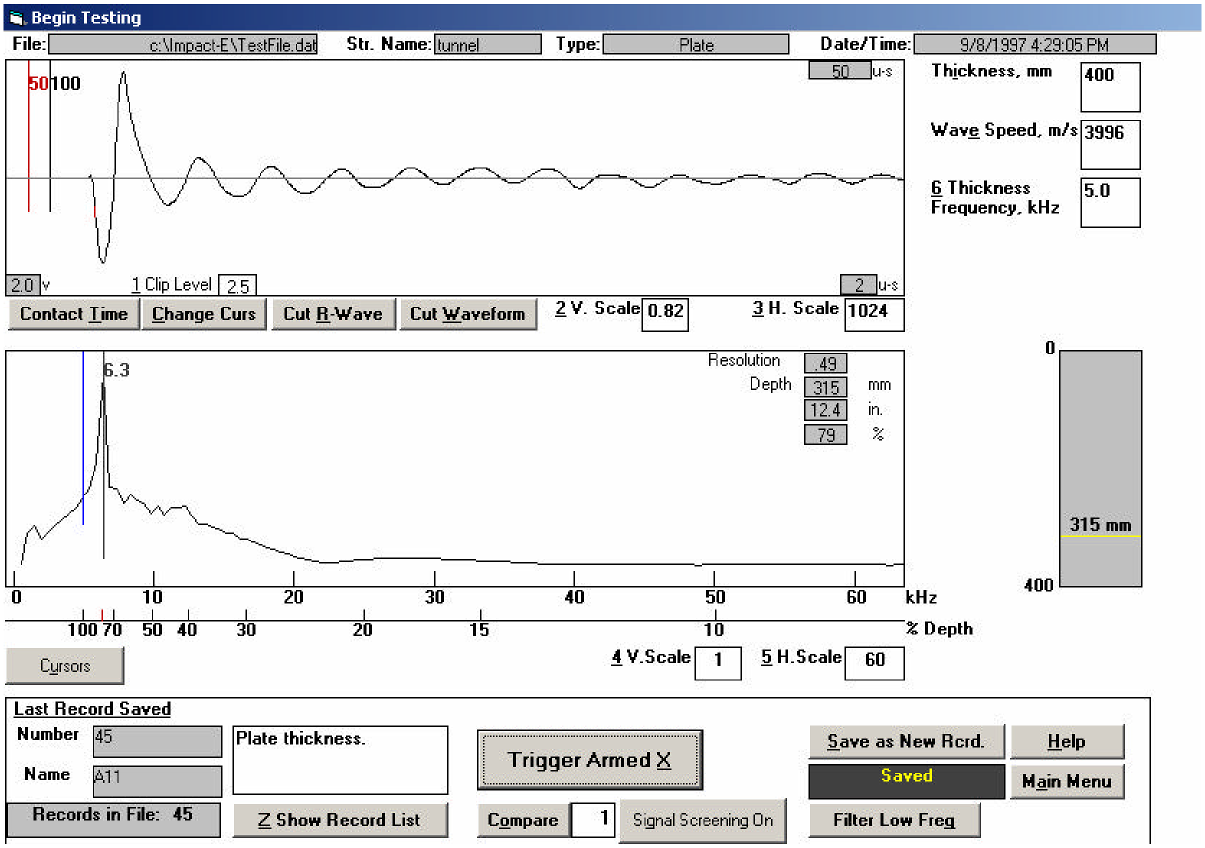

Figure II-15. The results of a test to determine the thickness of a plate as they appear on the computer screen immediately after the impact.

27. Click **Main Menu** at the lower right of the screen [Keyboard: press "**Alt+a**"], and on the **Main Menu** screen, click **Exit** [Keyboard: press "**Alt+x**"] to close the program.

This completes Section II of this tutorial, covering the procedure for setting up the impact-echo test system, opening the software program, initializing the system, and preparing for an impact-echo test. Repeat the numbered action steps in this section, experimenting with different features of the software, until you are thoroughly familiar with the topics covered.

The next section of the tutorial describes the use of the **Examine Test Data** screen, and explains how the user interacts with the software using command buttons, text boxes, moveable cursors, and other interactive features.

SECTION III: Learning About the Software

Introduction

This section describes the principal features of the software through a series of steps that display and examine the important screens that appear during testing and evaluation of test data.

Most user interactions with **Impact-E** or **ImpactDemo** can be accomplished with a mouse or from the keyboard. In the instructions that follow, the use of a mouse is assumed. The phrase "click **X**" instructs the user to place the mouse pointer on object **X** and press the left mouse button. Instructions for using the keyboard are shown in brackets, as in [Keyboard: press "**Alt+O**"].

Start the Program

1. On the Windows screen click **Start** and **Programs** to open the list of program groups. Click the **Impact Echo** group, and click **ImpactDemo** to start the program. [Keyboard: press the "**Windows**" key (not on all keyboards), press "**P**" to open the list of program groups, and use the up/down arrow keys to select the program group named **Impact Echo.** Press **Enter** to display the list of programs, and use the up/down arrow keys to select the program named **ImpactDemo**. Press **Enter** to start the program.]

Open an Existing Data File

2. On the **Main Menu** screen, click **Open Test Data File** [Keyboard: press "**Alt+O**"]. On the **Default File** screen, click **Continue.** On the **Open Test Data File** screen, the **c:** drive is active and the **Directory** box is selected.

3. In the **Directory** box find the directory **ImpactDemo** (use the scroll bar if necessary) and *double* click **ImpactDemo** to display the data files it contains. [Keyboard: press "**Alt+r**" to select the **Directory** box, use up/down arrows to select **ImpactDemo,** and press **Enter** to display the files.]

4. In the **File Name** box, double click the file **TestFile.dat** to open it, and click **OK** in the message box to return control to the **Main Menu** screen. [Keyboard: press "**Alt+N**" to select the **File Name** box, use up/down arrows to select file named **TestFile.dat** and press **Enter** and **Enter** again to open it. Press **Enter** to close the message box.]

Learning the Features of the Examine Test Data screen

5. On the **Main Menu** screen, click **Examine Test Data** [Keyboard: press "**Alt+E**"] to open the **Examine Test Data** screen (Figure III-1). The first record (test point) in the file is displayed. The principal features of this screen are the two graphs. The upper graph is the waveform, the voltage-time graph that describes the surface displacements from this test. The lower graph is the amplitude spectrum, which identifies the principal frequencies in the waveform. The interpretation of these graphs is explained in detail in later sections. (See also Chapters 4 and 5 in *Sansalone and Streett*.) The objects on this screen (command buttons, text boxes, labels, etc.) are described in the following paragraphs.

   In addition to the two graphs, there are five classes of objects on this screen that display information and/or allow the user to interact with the program:

- **Command Buttons** - gray rectangles with 3-D borders. These are standard Windows command buttons. At the base of the upper graph are command buttons labeled **Contact Time, Change Curs, Cut R-Wave,** and **Cut Waveform.** In the large rectangle at the bottom of the screen are command buttons labeled **Next Record, Save as New Record, Prepare to Print, Help,** etc. A command is activated by clicking the button with the mouse, or from the keyboard by pressing the **Alt** key together with the key of the underlined character in the caption on the button.[5]

  Example: At the bottom of the screen is a command button labeled **Z Show Record List**. Click this button with the mouse [Keyboard: press "**Alt+Z**"]. A list of all records in the open file appears on the screen and the caption on the button changes to **Z Hide Record List**. Click the button again to hide the list. The functions of other command buttons are explained later in the tutorial.

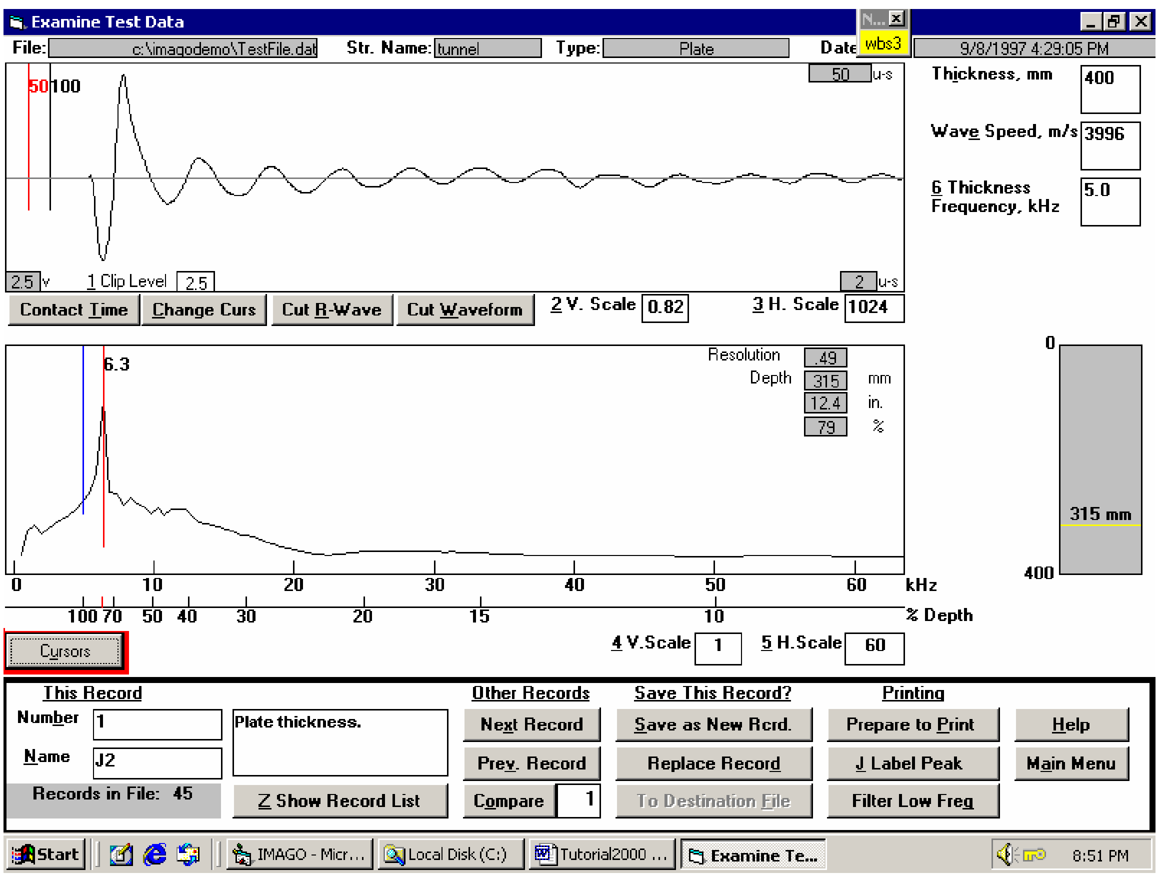

Figure III-1. A test record on the **Examine Test Data** screen.

[5] In standard Windows protocol, activating a command or selecting an object from the keyboard requires that the **Alt** key be pressed together with the underlined character in the caption.

- **Fixed Labels** - labels in white lettering on a gray or blue background (in the figures in this manual black lettering not in a box) that describe adjacent text boxes or information labels.
  Example: in the upper right of the screen, the Fixed Label "Thickness, mm" identifies the contents of the adjacent text box.

- **Information Labels** - gray boxes with a narrow black border, containing a variable associated with the test record displayed on the screen. These boxes are not interactive—that is, the information they contain cannot be changed directly by the user.
  Example: the box labeled "**Date/Time**" in the upper right corner of the screen contains the date and time that the test shown in this record was performed, in the format **month/day/year hour:minute:second (AM or PM)**.

- **Text Boxes** - boxes with a white background that contain information about the test record displayed. Text boxes are interactive. The information they contain can be changed by the user. To enter information into a text box, select the box by clicking on it with the mouse [Keyboard: press the "**Alt**" key plus underlined letter or number in the fixed label next to the box]. After the desired text is entered into the box, ***the Enter key must be pressed to transfer new text into the computer memory.***
  Example: At the lower right of the upper graph, the number **1024** in the box labeled "**3 H. Scale**" is the number of digitized data points used to plot the waveform (the voltage-time signal).

- **Moveable Cursors** - vertical lines on the waveform and spectrum that can be moved horizontally across the graphs using the mouse or keyboard. There are two cursors on the waveform (the upper graph) and one on the spectrum. The numbers on the waveform cursors give the time in microseconds after the trigger point, while the number on the spectrum cursor gives the frequency of the cursor position in kiloHertz (kHz).

  Example: Place the mouse pointer at about the midpoint of the waveform and click the left button. The active (yellow) cursor moves to that position. Double click on the active cursor or click the **Change Curs** button [Keyboard press "**Alt+C**"] to make the other cursor active (yellow). Place the mouse pointer at another point on the waveform and click the left button. The active cursor moves to that position. [From the keyboard, use the **{"'}** key—at the right of the 3rd row from the bottom of the keypad—to move the active cursor from peak to peak to the right. Use the **{Kk}** key to move it peak to peak to the left. The two keys in between, **{Ll}** and **{:;}** move the active cursor left or right in small steps. Holding any of these keys down causes continuous movement. Do not use the "**Alt**" key with these keys to move the cursor.

  The cursor on the spectrum is moved in the same way. The four keys used to move the spectrum cursor are just below those used to move the waveform cursors. To move the spectrum cursor peak to peak, use the **{Mm}** and **{?/}** keys; to move it in small steps use the **{<,}** and **{>.}** keys. Although it is easy to position the cursors using the mouse, there are times when the keyboard must be used. It is important to experiment with moving the cursors with the keyboard, and changing the active cursor on the waveform, to become familiar with this feature of the display.

The Critical Parameters: Thickness, P-Wave Speed, and Frequency

In impact-echo tests on plate structures, the three critical parameters are thickness **T**, P-wave speed **Cp**, and frequency **f**. These Parameters are displayed in text boxes in the upper right corner of the screen. For a test on a solid portion of a plate, these three parameters are related through the equation **T** = 0.96**Cp**/(2**f**).[6] This is the fundamental equation of impact-echo testing for simple plate structures. If two of the three parameters are known, the third can be calculated.

The Waveform

6. Learn the features of the waveform. The waveform (upper graph) is a plot of the voltage-time signal from the transducer. Because the voltage output of the transducer is proportional to displacement normal to the surface, this graph describes displacements at the point of contact between the transducer and the surface. These displacements are caused by the arrival of stress waves generated by the impact and reflected from the external boundaries or flaws within the structure. Multiple reflections of stress waves within a structure give rise to periodic displacements. The frequencies of these displacements appear as peaks in the amplitude spectrum (the lower graph), and they provide information about the dimensions of the structure and depths of flaws. It is important to understand the features of the waveform and to learn how to interpret the information it contains.

7. Examine the fixed labels (gray boxes) that contain information about this test record:

   - **Voltage.** The number in the gray box in the lower left corner is the voltage range selected when the data acquisition parameters were set (see Appendix **A**). It is the maximum absolute voltage accepted by the data acquisition system. To take full advantage of the 14-bit resolution of the data acquisition system, the voltage should be set just above the maximum value expected in the signal. In most cases a voltage range of ±1 volt works well. For very smooth concrete surfaces, which produce strong responses, a setting of ± 2 volts is sometimes appropriate.

   - **Sampling Interval.** The gray box in the lower right corner gives the sampling interval, or time between samples, in microseconds (μs). This is the time interval at which the voltage signal from the transducer is digitized by the data acquisition system. The sampling rate is the reciprocal of this number. If the sampling interval is 2 μs, for example, the sampling rate is 1/0.000002 = 500,000 samples per second, usually stated as 500 kHz (kiloHertz) or 0.5 MHz (MegaHertz). The time between samples is set on the Parameters for Data Acquisition screen (Appendix **A**).

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[6] The general equation is T = b **Cp/(2f)**, where b is a "shape factor" dependent upon the geometry of the structure. For simple plate structures, b = 0.96, and it is customary to use the quantity 0.96**Cp** as the "apparent P-wave speed in a plate", sometimes written **Cp,plate**, so that the equation reduces to **T** = **Cp,plate** /(2**f**). This is done in part because in early work on impact-echo the existence of the "shape factor", b, was unknown, and the simpler equation was used. See *Sansalone and Streett*, pp. 50-52.

- **Cursor to Cursor.** The number in the gray box in the upper right corner of the screen is the time, in µs, separating the two cursors on the waveform. It changes when either of the cursors is moved. The use of this number is explained later.

8. Examine the three text boxes (white backgrounds) within or below the waveform. These are interactive boxes, whose contents can be changed when the program is running.

   - **Horizontal Scale.** The integer in the **3 H. Scale** text box at the lower right of the waveform is the horizontal scale, or the number of data points plotted in the waveform. It is normally expressed as a power of 2 (2048, 1024, 512, etc.) to facilitate the mathematical calculations that produce the spectrum. When impact-echo tests are performed with Impact-E, ***2048 digitized data points are always recorded and stored as a permanent part of the test record***. The number in the **3 H. Scale** text box is the number of points plotted on the screen (usually 1024) and used to calculate the spectrum.

     Example: Click the **3 H. Scale** text box [Keyboard: press "**Alt+3**"]. The number in the box is selected, and can be changed by entering another number. Enter 2048, and press **Enter**. The waveform is re-drawn using 2048 data points, and the spectrum is re-calculated using this number.

   - **Vertical Scale.** The number in the text box labeled **2 V. Scale** defines the vertical range of the graph on which the waveform is plotted. It is expressed in volts, and is automatically set so that the maximum absolute voltage in the signal reaches the top or bottom of the graph. The vertical scale cannot be changed by the user.

   - **Clip Level.** The number in the text box labeled **1 Clip Level,** in the lower left of the graph, is a voltage value that is used to "clip" the waveform – that is, to remove voltages with an absolute value greater than this number. The default setting is 2 volts.

     Example: Click the **1 Clip Level** text box [Keyboard: press "**Alt+1**"], enter 0.2 as the clip level value, and press **Enter**. Voltages above +0.2 and below -0.2 are clipped (removed) from the waveform, and the vertical scale is reset to 0.2v. The effect is similar to cutting or removing the entire R-wave. (See examples in Sectons VII and VIII.) The advantage of clipping is that in testing situations where the R-wave is very large relative to the remainder of the signal, the clip level can be set at an appropriate level, and the R-waves will be automatically "clipped" (partially removed) in each test. (See *Sansalone & Streett*, pp. 58-59.)

9. Learn to measure the contact time. The **Contact Time** command is used to facilitate measurement of the width of the R-wave, the region of negative voltage at the beginning of the waveform. The R-wave (or Rayleigh Wave) is a surface wave that propagates outward from the impact point like a ripple in a pond. The width of the R-wave—the time between the two points where it crosses the zero voltage line—is a measure of the contact time, the length of time that the impacting sphere is in contact with the concrete surface. The contact time is a function mainly of the diameter of the sphere, and it determines the maximum useful frequency in the signal. (See Chapters 3, 4 and 24 in *Sansalone and Streett*.)

Example: Click **Contact Time** [Keyboard: press "**Alt+T**"]. A gray box appears with information about the contact time, the sphere diameter, and implications for testing. The software attempts to place the two cursors at the points where the R-wave intersects the horizontal line, but it is not always successful. To adjust the cursors more precisely, click the **Adjust Cursors** button and click **Change Curs** to select one of the cursors to be moved [Keyboard: press "**Alt+A**" and "**Alt+C**"]. Move the cursor with the mouse or keyboard as explained under **Moveable Cursors** above. The contact time for this record is about 50 μs. After positioning the cursors, click **Contact Time** [Keyboard: press "**Alt+T**"] to return to the previous display. Click **Exit** [Keyboard: press "**Alt+X**"] to return to the **Examine Test Data** screen without saving the contact time, or click **Save Contact Time** [Keyboard: press "**Alt+S**"] to save the contact time as a permanent part of the record and display it in the lower portion of the waveform.

10. Double click on the active (yellow) cursor, or click **Change Curs** [Keyboard: press "**Alt+C**"] to make the other cursor active on the waveform. Only the active cursor can be moved using the mouse or keyboard.

11. Learn to use the **Cut R-Wave** command. This is useful in removing the R-wave when its amplitude is large relative to the remainder of the waveform.

    Example: Using the mouse or keyboard, place the active cursor on the zero in the waveform at about 330μs, and click **Cut R-Wave** [Keyboard: press "**Alt+R**"]. That portion of the waveform to the left of the active cursor (resulting from the passage of the Rayleigh or surface wave) is removed, and the frequency content of the remainder is calculated and displayed in the spectrum. (It is the initial negative trough that mirrors the force-time function of the impact. The large positive peak that follows is an inertial effect.) The caption on the button changes to **Restore R**. Clicking this button again restores the full waveform and recalculates the spectrum. Click this button several times, and observe the changes in the spectrum. When the leading, high-amplitude portion of the waveform associated with the R-wave is removed, the main peak in the spectrum becomes sharper. For an example of useful R-wave removal, see the discussion of record 25 in Section VIII.

12. Learn to use the **Cut Waveform** command, used to remove (set equal to zero) that portion of the waveform to the right of the active (yellow) cursor.

    Example 1: Restore the R-wave if it has been cut, set the active cursor to the point where the waveform cuts the zero voltage line (the horizontal line) at 330 μs, and click **Cut Waveform** [Keyboard: press "**Alt+W**"]. The waveform to the right of the cursor is set to zero, the caption on the button changes to **Restore W**, and the spectrum is re-calculated, showing a broad dome of frequencies associated with the leading, high-amplitude portion of the waveform caused by the R-wave. When the amplitude of the R-wave is large compared to the remainder of the waveform, this dome of frequencies becomes a prominent part of the spectrum, and can obscure the important peaks. (See *Sansalone and Streett*, pages 58-59.) These effects are subdued in this test record. For further discussion of R-wave removal, see the analysis of record 25 in Section VIII.

Example 2: The combination of the **Cut R-Wave** and **Cut Waveform** commands can be used to determine the frequency content of any portion of the waveform. Click **Restore W** to restore the full waveform. Place the active cursor at about 600 µs, and click **Cut R-Wave**. Place the cursor at about 1600 µs, and click **Cut Waveform**. The resulting spectrum shows the frequency content of the waveform between 600 and 1600 µs after the trigger point.

The Spectrum

13. Examine the spectrum. The spectrum (lower graph) is a plot of amplitude vs. frequency, showing the distribution of frequencies in the waveform. It is calculated from the waveform by a mathematical function called a Fourier transform. Because the waveform is stored in the computer as a two-dimensional array of voltage vs. time, the transformation is carried out numerically, using a technique known as a Fast Fourier Transform, or FFT. (See *Sansalone and Streett* Chapter 5, "Frequency Analysis".) Calculating the spectrum is sometimes referred to as transforming the signal from the time domain (the time-displacement graph called the waveform) into the frequency domain (an amplitude-frequency graph called the spectrum).

    The significance of the spectrum can be explained as follows. If one were to assemble a group of sine waves, with amplitudes and frequencies represented by points on the spectrum, and add all these together, the result would be the waveform. In other words, the height of the spectrum at any frequency gives the amplitude of a sine wave of that frequency that is a component of the waveform. If the waveform is a single sine wave of frequency **f** and amplitude **A**, the spectrum is a spike of height **A** at frequency **f**. A waveform produced by multiple reflections of stress waves, using the impact-echo method, contains periodic components but is not a pure harmonic function like a sine wave. When the waveform is transformed into the frequency domain by the FFT the result is a continuous distribution of frequencies, in which the dominant periodic components appear as sharp peaks. The frequencies of these peaks are used with the P-wave speed to calculate dimensions of the structure or depths of flaws.

    Examine the fixed labels, text boxes and command buttons within or beneath the spectrum. Consider first the fixed labels (the gray boxes in the upper right corner of the spectrum graph).

    - **Resolution** is frequency resolution—the spacing or discrete difference between frequency points on the spectrum, in kHz. It determines the precision with which thickness or depth can be determined. The resolution is 1/**(n**D**t)** where **n** is the number of points in the waveform (1024 for this record) and D**t** is the sampling interval (2 µs for this record). The quantity **n**D**t** is the record length, or the length of time over which the signal is recorded. The resolution can be improved by increasing **n** or D**t**, but there are practical limits. The maximum value for **n** is 2048, but 1024 works well for most testing. Values of D**t** between 2 and 4 µs usually provide the best results. Because the transient resonant vibrations induced by an impact decay very rapidly, it is seldom useful to increase the record length beyond about 8 milliseconds (**n** = 2048, D**t** = 4 µs). For more information about frequency resolution, see Appendix **A** in this manual and *Sansalone and Streett*, pp. 64-65.

- **Depth** is shown in the remaining three gray boxes in mm, inches, and per cent of full thickness. In calculating the per cent thickness, the full thickness is the value entered when testing begins (or calculated later from test results). It is displayed in the text box at the upper right of the screen.

  Example 1: The relationship between depth **d**, frequency **f,** and wave speed **Cp** is **d =** b**Cp/2f**, where b is a "shape factor" characteristic of the geometry. For a plate structure, b = 0.96, and the quantity 0.96**Cp** is sometimes called "the apparent P-wave speed in a plate", or **Cp,plate** (see footnote 6 on page 29). The reciprocal relationship between **d** and **f** causes the uncertainty in depth due to the limited resolution in the spectrum to increase sharply at low frequencies. To illustrate this, place the spectrum cursor on the peak at 6.3 kHz, and note that the corresponding depth is 315mm. Moving the cursor one digital point above and below this peak (to 6.8 and 5.9 kHz) using the **{>.}** and **{<,}** keys, shows the corresponding depths to be 292mm and 341mm, respectively. Therefore, the uncertainty in depth at this level, due to the resolution of 0.24 kHz, is about 24mm, or 7 per cent of the nominal depth of 315mm. Now move the spectrum cursor to 20 kHz. The depth corresponding to this frequency is 100mm, and the uncertainty due to the frequency resolution of 0.49 kHz is 2-3mm or 2-3 per cent of the nominal depth. This is a subtle point that is sometimes difficult to grasp. Experiment with moving the cursor back and forth, and observe how the change in depth associated with a change of one digital point in the spectrum increases as the frequency decreases.

  Example 2: There is a % Depth scale beneath the spectrum, in light blue, with a small yellow cursor that moves in tandem with the cursor on the spectrum. The position of the cursor on this scale indicates the per cent depth. Placing the spectrum cursor at 20 kHz, for example, shows that a peak at this frequency would correspond to a depth of about 25% of the full thickness.

- **Vertical and Horizontal Scales.** The spectrum is a plot of amplitude (vertical scale) vs. frequency (horizontal scale). With the vertical scale set at 1, the spectrum is normalized to make the height of the highest peak equal to 80% of the height of the graph. The default value of the horizontal scale is 60 kHz. There is seldom a need to change the vertical scale. If the important frequencies in the spectrum are at low values, the horizontal scale can be decreased to 20 to 40 kHz to show more detail.

- **Cursors command button.** When this button "has the focus" it is highlighted by a red border, and the cursors on both the waveform and spectrum can be moved with the mouse or the keyboard. (See **Moveable Cursors** above.)

The Depth Box for Plate Structures

14. Examine the depth box for plate structures. When the structure being tested is a plate or plate with overlay, a gray rectangle appears to the right of the spectrum, representing a cross-section of the structure. The top of this box represents the impact surface (depth 0) and the bottom a depth equal to the full thickness (400mm in this example). When the spectrum cursor is moved a similar cursor within this box (a horizontal yellow line) moves in tandem. The number on this line is the depth within the plate corresponding to the frequency of the cursor

on the spectrum. If the spectrum cursor is moved to a frequency below the thickness frequency—the frequency associated with P-wave reflections between the top and bottom of the plate—the horizontal cursor disappears from the depth box, the caption on the box changes to “Cursor Out of Range”, and the depths indicated in the gray boxes in the upper right of the spectrum appear in red. The significance of peaks at frequencies below the thickness frequency is discussed in a later section.

The Control Panel at the Bottom of the Screen

15. Examine the controls at the bottom of the screen. The rectangular control panel at the bottom of the screen contains a variety of labels, text boxes and command buttons. These will be explained starting from the left.

 - The **Number** and **Name** text boxes. These contain the number and name of the record displayed on the screen. They can be used to call up records in the open file by number or name. To display record 3 for example, click the **Number** text box [Keyboard: press “**Alt+b**”], enter “**5**”, and press **Enter**. Record 5 is displayed. A similar procedure is followed to display a record using its name. Entering a number greater than the number of records in the file, or a name that is not in the record list, will result in an error message.

 - The information label, **Records In File: n**, at the lower left of the control panel indicates the total number of records in the open file. It is not interactive.

 - **The Description Text Box.** The large text box to the right of the number/name text boxes contains a brief description of the record (40 characters maximum). This description is normally entered when the test record is saved, but it can be changed when the record is examined. Click this text box to open it [Keyboard: press the **Tab** key repeatedly until the box is highlighted by a red border]. A new or modified description can be entered. Press **Enter** to save it to the data file.

 - Click the **Z Show Record List** command button [Keyboard: press “**Alt+Z**”]. A list of all records in the file appears on the screen, and the caption changes to **Z Hide Record List**. The record list that appears is interactive. To open any record on the list, double click that record [Keyboard: use the up/down arrow keys to select the desired record, and press **Enter]**. The record list disappears, and the selected record is displayed. To remove the record list without opening a new record, click **Z Hide Record List** [Keyboard: press “**Alt+Z**”].

 - Click the **Next Record** and **Prev. Record** buttons [Keyboard: press “**Alt+X**” or “**Alt+V**”] to access the next record or previous record in the data file.

 - **Comparing Records.** Click the text box next to the **Compare** button [Keyboard: press the **Tab** key repeatedly until the box is highlighted], enter the number 5, and click **Compare** or press **Enter**. The spectrum for record 5 is overlaid on that of the open record as a green dashed line, and the caption on the button changes to **Remove**. This is useful for comparing records during routine testing. Once the response of the solid structure is known, it can be used as a comparison record for subsequent tests. Significant

departures from the solid response are an indication of a flaw. More about this later. Click **Remove** [Keyboard: press "**Alt+O**"] to remove the comparison spectrum.

- Click **Save as New Rcrd**. [Keyboard: press "**Alt+S**"] to open the **Save to Data File** screen, used for adding records to the open data file. This is most often used during testing, but it can also be used when examining test data. The information at the top of the **Save to Data File** screen informs the user of the path and name of the open data file and the number that will be assigned to this record if it is saved to the file. (Saved records are always added to the end of the file, and numbered sequentially.) To select a text box or command button, press **Tab** until the desired object is highlighted. A suggested record name appears in the **Record Name** text box. This suggested name is produced by incrementing the letter or number at the end of the name of the current record. In this case the current record is named J2, and the suggested name for the record to be saved is J3. If the open record had been named 2J, the suggested name would be 2K. This makes it convenient to use a logical sequence of record names during testing. If the first record is named **MyTest1**, for example, subsequent records will automatically be named **MyTest2, MyTest3, MyTest4**, etc., unless the suggested name is changed before the record is saved. After entries have been made in the **Record Name** and **Description** text boxes, click **Accept** to save the current record as a new record, or click **Cancel** to return without saving the record. [Keyboard: press "**Alt+A**" or "**Alt+C**"].

- To replace the current record in the file with information on the screen, click **Replace Record** [Keyboard: press "**Alt+D**"]. A **Yes/No** text box appears. Click **Yes** to proceed or **No** to cancel [Keyboard: press "**Alt+Y**" or "**Alt+N**"]. This command is useful for saving as a permanent part of the record new values for parameters that have been changed on the screen, such as horizontal scales, P-wave speed, thickness, etc.

- The **To Destination File** button is used to copy the record displayed on the screen to another file, called the destination file, that has been opened using the **File Utilities** system (described later in this section). At this point the **To Destination File** button is disabled, because a destination file has not been opened. This command provides a means of creating a new data file by copying test records from one or more existing files.

- **Prepare to Print** (See "Printing Waveform and Spectrum" below.)

- Place the spectrum cursor on the highest peak (6.3 kHz) and click **J Label Peak** [Keyboard: press "**Alt+J**"]. The letter "**x**" is placed at the top of the peak, and the frequency (6.3 kHz in this case) appears next to it. Up to ten peaks can be labeled in this fashion, and the labels will appear on printed copies of the record. The labels are not saved, and will not reappear when this record is next accessed.

- The **Filter Low Freq.** button is used to activate a digital filter that mathematically filters (removes) frequencies below the frequency marked by the current position of the spectrum cursor. This is especially useful for removing an artificial signal associated with the natural resonance of the transducer unit, which is about 1 kHz. Open record 19 (click on the box in the lower left labeled **Number** [Keyboard: press "**Alt +b**"]. This record

shows a large peak at 1.5 kHz in the spectrum. This results from the slow oscillation of the waveform around the zero. Place the spectrum cursor at about 4 kHz, and click **Filter Low Freq**. [Keyboard: press "**Alt+q**"]. Observe the change in the waveform, which now appears as a decaying sine wave, dominated by a single frequency. The caption on the button has changed to **Restore Low Freq.** Click on this button several more times and observe the changes in the waveform with the removal and restoration of the low frequency components. This command must be used with care, to avoid removing important frequencies from the waveform. Its proper use is explained later in this manual.

Printing Waveform and Spectrum

If your computer has a printer connected to the printer port, copies of the waveform and spectrum can be printed from records in the open file.

16. Click **Prepare to Print**, to open the **Prepare Graphs for Printing** Screen (Figure III-2). This screen permits the user to preview the waveform and spectrum, add text to the graphs, and send images to a printer connected to the computer. In addition to the **Help** button (explained earlier) there are six command buttons and one interactive text box on the screen:

- Click **Printer Setup** [Keyboard: press "**Alt+N**"] to open a screen that provides several options for adjusting the size and character of the printed graphs. These options are self-explanatory.

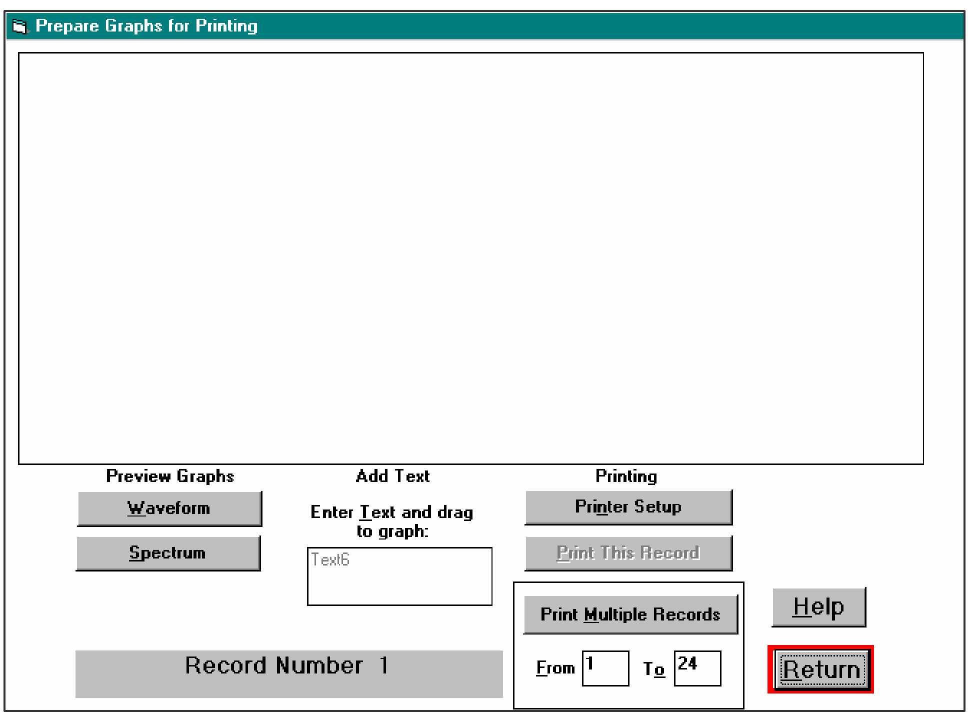


Figure III-2. The **Prepare Graphs for Printing** screen

- Click **Waveform** [Keyboard: press “**Alt+W**”] to preview the waveform before printing.

- Click **Spectrum** [Keyboard: press “**Alt+S**”] to preview the spectrum before printing.

- After one or both graphs have been previewed, the **Print This Record** button is enabled. Click **Print This Record** [Keyboard: press “**Alt+P**”] to print the graphs that have been previewed using the **Waveform** and **Spectrum** commands.

- To print a consecutive group of records from the open file, click the **From** and **To** text boxes [Keyboard: press “**Alt+F**” and “**Alt+O**”] and enter the beginning and ending numbers of the records to be printed. Click **Print Multiple Records** [Keyboard: press “**Alt+M**”] to initiate printing. The waveform and spectrum for each record will be printed, each record on a separate page.

- To add text to a graph displayed on the screen, click the text box beneath the caption **Enter Text and drag to graph** [Keyboard: press “**Alt+T**”] and enter the desired text in the box. Place the mouse pointer anywhere in the box and hold down the left mouse button while the box is “dragged” to the graph above. Ignore the box outline. When the mouse button is released, the text will be placed on the graph, with the lower left corner of the text at the tip of the mouse pointer. If you make a mistake, click **Waveform** or **Spectrum** again and start over. Text added to the graphs will appear in printed copies.

- Click **Return** [Keyboard: press “**Alt+R**”] to return to the **Main Menu** screen when printing is completed.

The File Utilities System

The **File Utilities** screen is accessed by activating the **File Utilities** button on the **Main Menu** screen. It permits the user to send summaries of sets of test records to an Excel Spreadsheet or to a printer, change parameters such as wave speed or thickness for sets of test records, copy records between files, and copy test records to ASCII files or directly to Excel Spreadsheet. The **File Utilities** screen is illustrated in Figure III-3.

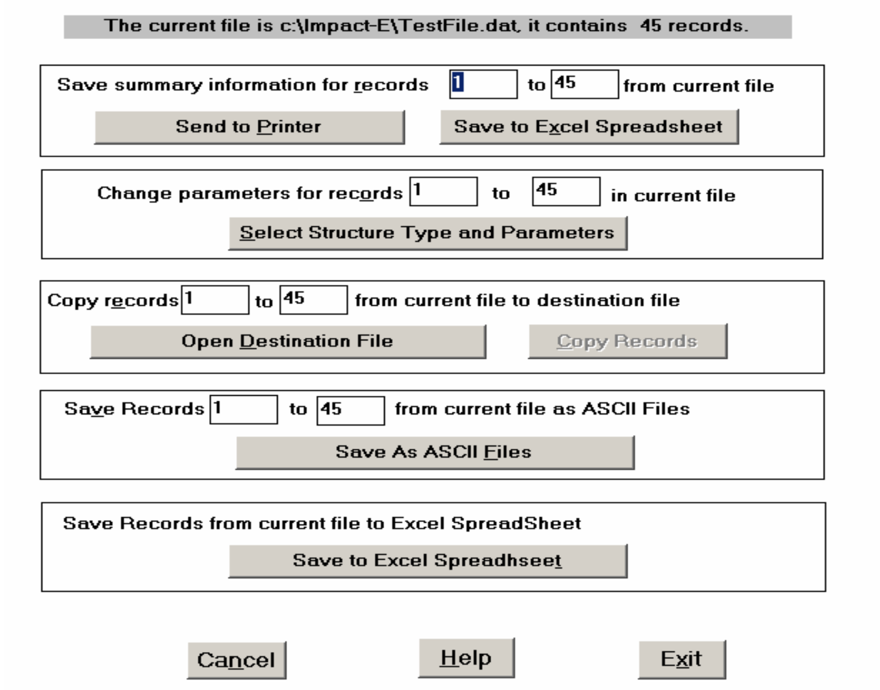


Figure III-3. The **File Utilities** screen.

The name of the current file, which can be acted upon by the commands on this screen, is shown at the top of the screen.

Sending Summary Information for Records to Printer or Excel Spreadsheet.

Activating the **Save to Excel Spreadsheet** button will open another screen that allows a summary of all records in the current file to be sent to an Excel Spreadsheet. (Microsoft Excel software must be installed on the computer.) The summary is in the form of a table that includes the following information for each of the records in the range covered by the numbers in the text boxes above the button,:

record number,
test point name,
structure type (plate, plate/overlay, circular column, etc.),
wave speed(s),
thickness or dimension(s) of the structure, and
description saved with the record.

The file name, structure name, and test date will appear at the top of the table. This provides a condensed summary of a large number of test records in a file.

Activating the **Send to Printer** button will cause this information to be sent to a printer, if one is connected to the computer.

Changing Parameters for Records.

Activating the **Select Structure Type and Parameters** button calls up a screen (Figure III-4) that allows the user to select and change any of several parameters for a selected number of

records in the current file. The records to be changed will be those within the range specified by numbers in the two text boxes above the button. (The default numbers are those of the first and last records in the file.)

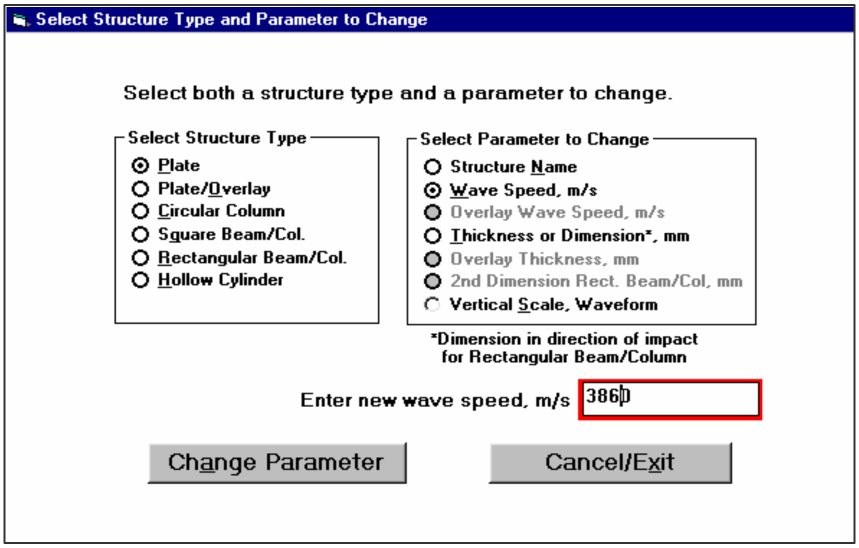


Figure III-4. The **Select Structure Type and Parameter to Change** screen.

The type of structure for which a parameter is to be changed is selected by clicking one of the option buttons in the box at the upper left. This will enable (make active) the appropriate parameter option buttons in the box at the right. In this example, a **Plate** structure has been chosen, so the only parameters that can be changed are **Structure Name, Wave Speed**, and **Thickness or Dimension**. (If **Plate/Overlay** is selected as the structure type, the additional parameter buttons **Overlay Wave Speed** and **Overlay Thickness** will also be enabled.) Selecting one of the buttons in the box on the right will cause the text box below to be enabled, and an appropriate instruction on what to enter will appear to the left of the box. (In this example the instruction is **"Enter new wave speed"**, and the number 3860 has been entered in the text box.) If the **Change Parameter** button is activated, all records of the selected record type (plate) will have the designated parameter changed to the new value on the screen. (In this case, the wave speed for all records in the current file, in the selected range, that are for plate structures, will be changed to 3860 m/s.) Wave speeds for records in that range in the current file for other types of structures (columns, beams, hollow cylinders, etc.) will remain unchanged.

Copying Sets of Records from the Current File to Another File (The "Destination" File). The two command buttons, **Open Destination File** and **Copy Records** allow sets of records within the range specified in the two text boxes above the buttons, to be copied from the Current File (the file identified at the top of the screen) to a second file. The second file, called the Destination File, is opened by activating the **Open Destination File** button, which calls up the **Open Test Data File** screen (see p. 17.). The Destination File can be a new or existing file. After the Destination File has been opened, activating the **Copy Records** button causes a **Yes/No** message box to appear, giving the names of the Current and Destination Files and the number of records to be copied. Selecting **Yes** will cause the copying to take place. This enables

the user to create new files from individual records or groups of records selected from different test data files. After a Destination File has been opened, the **To Destination File** button on the **Examine Test Data** screen will be enabled allowing the user to add to the Destination File the record currently displayed on that screen.

Saving Records to ASCII Files.

A sequence of records can be saved as ASCII files by entering the beginning and ending record numbers in the boxes above the **Save As ASCII Files** button, and activating the button. Another screen appears (Figure III-5). The drop-down box at the top allows the user to choose the drive (Hard Disk , Floppy Disk, etc.) to which the files will be saved.

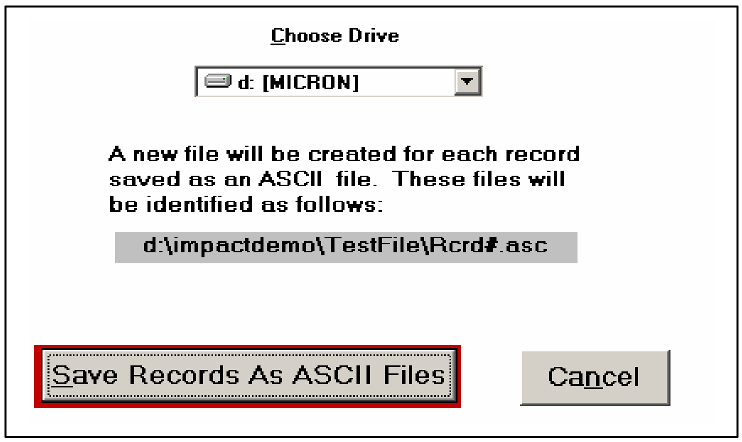


Figure III-5. Screen for saving test records as ASCII files.

For each record saved, a new file is created in the same directory as the test data file. The file name of the test data file becomes a subdirectory name and the ASCII file name is **"Rcrd#"** where **#** is the record number of the record being saved. The suffix **.asc** added to the file name to identify it as an ASCII file. For example, writing an ASCII file for record number 7 from the file **c:\ImpactDemo\TestFile.dat** will create an ASCII file of the waveform and spectrum, and save that file as **c:\ImpactDemo\TestFile\Rcrd7.asc**. ASCII files can be read directly into spread sheets or into other software programs for graphing or other purposes.

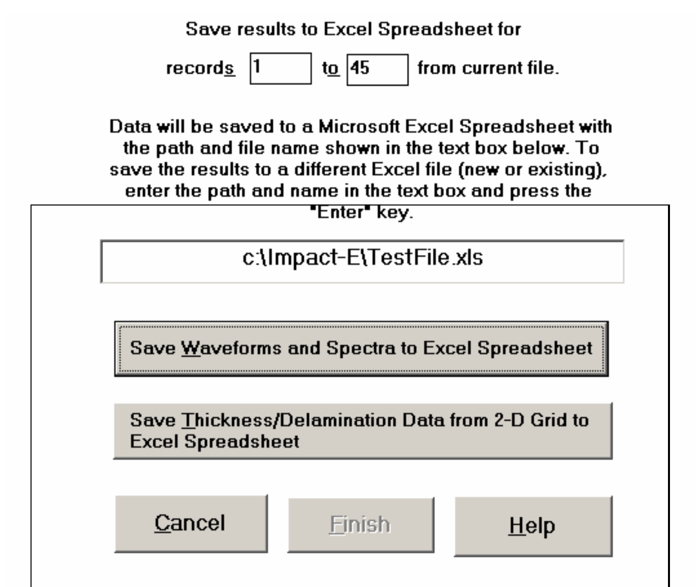
Saving records to a Microsoft EXCEL Spreadsheet.

You can create Microsoft Excel Spreadsheets using **Impact-E** or **ImpactDemo** software, but you must have Microsoft Excel software installed on the computer on which you open and use these files. There are three options for saving data from individual test records to an Excel Spreadsheet.

1. *Saving a Summary of Records for all or part of a data file.* On the File Utilities Screen (which is opened from the Main Menu) enter the beginning and ending numbers of the records to be included in the Summary of Records (the default setting includes all records in the file). Click **Save to Excel Spreadsheet** in the block at the top of the screen, to open the Excel Spreadsheet screen. The path and name of the Excel file where the information will be saved appears in a text box on the screen. To save the information

to a different Excel file, enter a path and file name in the text box and press Enter . (An Excel file should have the suffix ".xls".) Click **Save Summary of Records to Excel Spreadsheet**. A summary for each record, including the Record Number, Record Name, Structure Type, Wave Speed, Thickness, and Description, is written to the designated Excel spreadsheet, which is created if it does not already exist. The data file is identified at the top of the spreadsheet by the path and file name, the structure name (if any), and the date on which the file was created. You can open the spreadsheet to view it without shutting down the Impact-E program. For test records that are wave speed measurements, the wave speed calculated from the test results appears in the summary. For tests on plates with overlay (such as concrete with asphalt overlay) a second wavespeed and thickness are given for the overlay. For measurements of the depth of surface-opening cracks, the crack depth calculated from the test results appears in the summary.

2. *Saving waveforms and spectra.* On the File Utilities screen, click **Save to Excel Spreadsheet**, to open the Excel Spreadsheet screen (Figure III-6). On this screen, enter the beginning and ending record numbers for the range of records you wish to save. The path and name of the Excel file where the data will be saved appears in a text box on the screen. To save the information in a different file, enter the path and file name in the text box and press **Enter**. (An Excel file should have the suffix "**.xls**".) Click **Save Waveforms and Sprecta to Excel Spreadsheet**. The wave form and spectrum for each record in the specified range will be written as vertical arrays on a single Excel Sheet, with a blank column between records. For wave speed measurements, two waveforms are written to the spreadsheet. The time required to write the waveform and spectrum for one record to a spreadsheet is 5 - 10 seconds; therefore writing a large number of records can take several minutes. After a message appears indicating that the records have been entered on the spreadsheet, another group of records can be saved to the same spreadsheet by entering a second set of beginning and ending record numbers in the text boxes at the top of the screen, and clicking the button again. When all desired records have been saved, click Finish [keyboard: **Alt + f**]. The spreadsheet will be saved to the file named in the text box, and it can be opened by the Excel software on your computer.



Figjre III-6. The **Excel Spreadsheet** screen.

3. *Saving an array of points from a 2-D grid*. This method is designed to permit a 2-dimensional array of data points from a rectangular grid to be saved as a 2-d array in an Excel Spreadsheet. It is useful, for example, for recording thickness in a concrete slab or tunnel wall, or in recording the results from tests on a bridge deck to locate areas where a relatively thin layer of concrete is delaminated (separated from the main slab). To use this method, the array must be laid out using letters and numbers as follows: A1, A2, . . . An; B1, B2, . . . Bn; C1, C2,. . . Cn; etc. This means that the name of each record must be a letter followed by a number. If the first test is named A1, the computer will automatically name succeeding records A2, A3, etc. To begin column B, enter B1 as the record name for the first test in that column. It is not necessary for the named points to be recorded in sequence in the computer. As long as they are named according to points in the array, they will be properly sorted when saved to an Excel Spreadsheet. (Up to 26 lettered columns can be used [A to Z] and any number of rows.)

   Before saving data to a spreadsheet, place the spectrum cursor for each record at the peak in the spectrum that indicates the dominant response. For solid structures this will be the thickness frequency. When a delamination is present, the resulting flexural vibrations in the delaminated layer will produce a strong peak at a lower frequency. The entry for each element of the spreadsheet will be the thickness indicated by the position of the cursor and the known wave speed. If the indicated thickness at any point is substantially greater than the nominal thickness of the structure being tested, it is likely that the structure is delaminated at that point. For example, when testing an 8-inch (203mm) thick bridge deck with a wave speed of 4000 m/s, the nominal thickness frequency will be 9.8 kHz. Therefore a dominant frequency close to this value is to be expected when testing a solid portion of the deck. If the spectrum of a test record is characterized by a single dominant frequency of the order of 5 kHz or less (corresponding to a thickness of 400 mm or higher) the response is very likely to be that of a delaminated layer. (See Sansalone and Streett, Chapter 10, p. 99.)

   On the File Utilities screen, click **Save to Excel Spreadsheet**, to open the Excel Spreadsheet screen. On this screen, enter the beginning and ending record numbers for the range of records you wish to save. (Wave speed records and records for

structure types other than plates will be ignored.) The path and name of the Excel file where the data will be saved appears in a text box on the screen. To save the information in a different file, enter the path and file name in the text box and press **Enter**. (An Excel file should have the suffix "**.xls**".) Click **Save Thickness/Delamination Data from 2-D Grid to Excel Spreadsheet**. A message will appear stating that the 2-D array has been created on the spreadsheet (this process may take 10 to 20 seconds for a large array). To save a different set of records as part of the same array, enter the beginning and ending record numbers and click the button again. When all desired records have been saved, click Finish. The spreadsheet will be saved in the file named in the text box, and can be opened by the Excel software on your computer.

This completes Section III of this tutorial, covering the Examine Test Data screen, and controls available to the user to examine test records and print copies of the waveform and spectrum. Repeat the action steps in this section until you are thoroughly familiar with the topics covered.

The next section of the **ImpactDemo** program describes how impact-echo is used to measure P-wave speed and plate thickness.

Section IV: Measuring P-Wave Speed and Plate Thickness

Introduction

In impact-echo testing the equations used to calculate dimensions and flaw depths express these quantities as linear functions of P-wave speed **Cp**. Wave speeds in concrete typically vary from about 3500 to 5000 m/s. When the wave speed is unknown, 4000 m/s is a good starting estimate. The accuracy of the results is determined in part, therefore, by the accuracy with which **Cp** is known. P-wave speed can be determined using impact generated stress waves by two different methods: (1) measuring the travel time of a P-wave between two transducers a fixed distance apart on a concrete surface; and (2) performing an impact-echo test on a solid structure of known dimensions (preferably a plate of known thickness). In the second method the wave speed is calculated from the equation **Cp = 2fd/**b, where **f** is frequency observed in the test, **d** is the characteristic dimension (plate thickness, for example), and b is a known “shape factor” that characterizes the geometry of the structure. Both methods are described in this section. See *Sansalone and Streett*, Chapter 7.

ASTM Standard for Measuring P-Wave Speed and Plate Thickness Using Impact-Echo

An ASTM Standard Practice, C-1383-98a, entitled, “Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method” was first published in October 1998 and updated in April 1999. A copy is included as Appendix **B** in this manual. The methods outlined here are based on this standard.

Setup for Direct Measurement of Wave Speed Using Two Transducers

In this method the travel time of a stress wave (P-wave or R-wave) between two transducers a fixed distance apart on a concrete surface is measured. If the fixed distance is **L** and the travel time is D**t,** the speed is distance divided by time: **Cp = L/**D**t**. Figure IV-1 is a schematic diagram of the test set-up, and Figure IV-2 is a photograph of a wave speed measurement in progress.

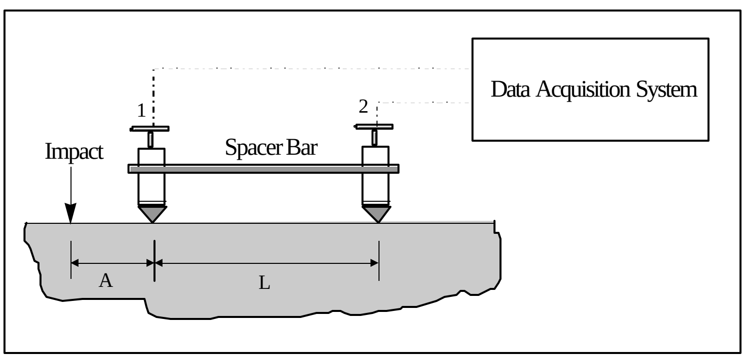


Figure IV-1. Schematic representation of test set-up for wave speed measurement.

Figure IV-2. Wave speed measurement

Both transducers are controlled by the same clock in the data acquisition system, making it possible to measure the elapsed time between the arrival of a stress wave at transducer 1 and its arrival at transducer 2. The numbered steps below show how this is done. In setting up the instrument for a wave speed test, transducer 1 (the transducer nearest the impact) is connected to Channel A on the data acquisition card and transducer 2 to Channel B. (The connections are made with BNC cable connectors.)

1. Start the **ImpactDemo** program and create and open a new file named **WaveSpd.dat**, on the **c:** drive in directory **ImpactDemo**. The complete path and file name will appear as **c:\ImpactDemo\WaveSpd.dat** (for instructions on opening a new file, see p. 16)**.** When control is returned to the Main Menu screen after the file is opened, click **Measure Wave Speed** to open the **Set-up for Wave Speed Measurement** screen (Figure IV-3).

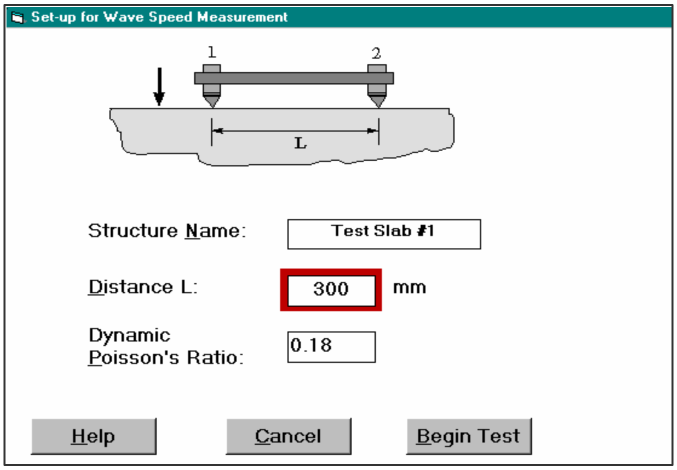


Figure IV-3. The **Set-up for Wave Speed Measurement** screen

Click the **Structure Name** text box and enter "**Test Slab #1"** as the structure name. Leave unchanged the default values of 300mm for **Distance L** and 0.18 for **Dynamic Poisson's Ratio**. Click **Begin Test** to open the **Wave Speed Measurement** screen (Figure IV-4). Default values for the sampling interval and voltage setting (see Appendix A) are 0.5 micro-seconds and 0.1 volts. If other values have been chosen, a message will appear asking the user to verify that other than the default values are to be used. The **Wave Speed Measurement** screen contains a single graph on which two waveforms are plotted when a wave speed measurement test is performed. Because a new file has been created and opened, the graph is blank. The green border around the **Trigger Armed X** button is flashing, indicating that the system is ready to receive the signals from a wave speed measurement test.

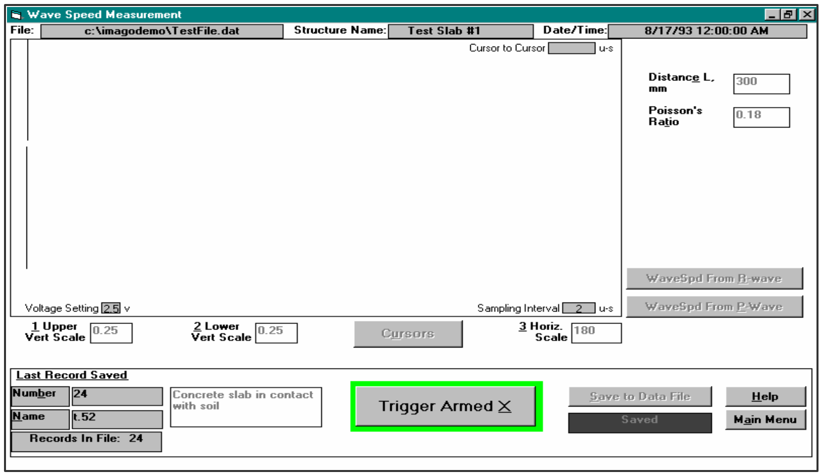


Figure IV-4. The **Wave Speed Measurement** Screen as it appears when a new or empty file has been opened.

2. To see the screen as it would appear after a wave speed measurement has been performed, click **Main Menu** to return to the **Main Menu** screen. Click **Open Test Data File**, and open the existing file **c:\ImpactDemo\TestFile.dat** (see Section III or click on **Help** for instructions on opening an existing file). Open record 2 in this file (Figure IV-5). It shows results of a wave speed measurement test on a concrete slab.

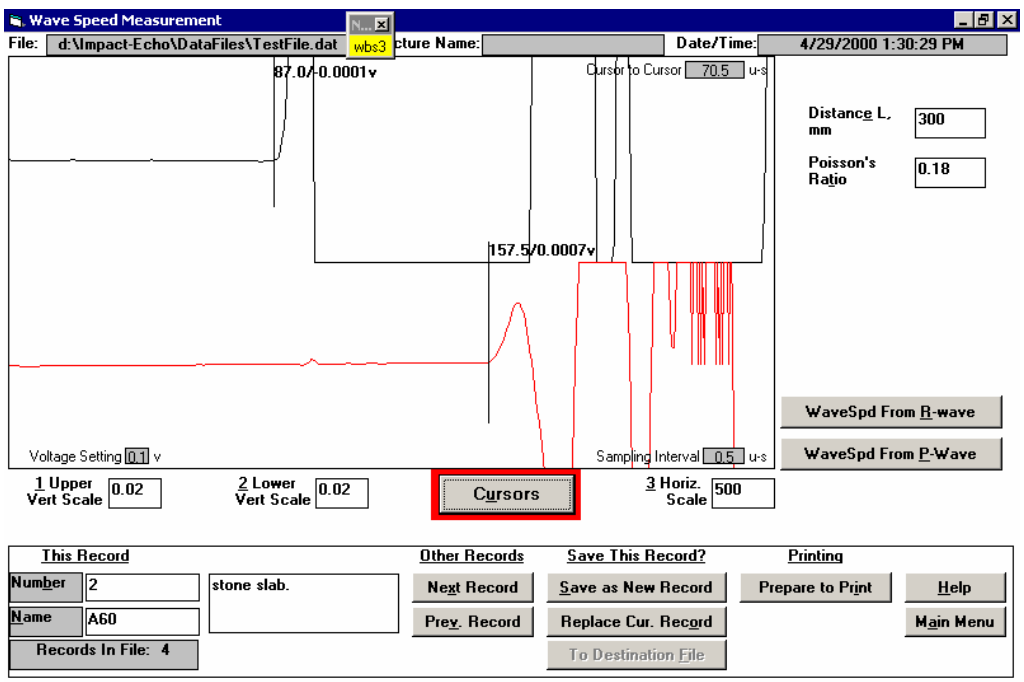


Figure IV-5. Test record for wave speed measurement. (Second record in file **c:\ImpactDemo\TestFile.dat**).

The upper waveform on the graph is from the transducer nearest to the impact point. The distance **L**, separating the two transducers is 300mm in this case, shown in upper right of screen. Each waveform has one cursor, labeled with two numbers separated by a slash. The

first number is the time in µs from the trigger point, and the second is the voltage of the transducer signal at that point. Note that the vertical scales for both graphs have been set to ±0.02 volts, for the purpose of identifying the first arrival of a signal (the passage of the P-wave) at each of the transducers. The structure in the leading part of each waveform is electrical "noise" in the system.

Measuring the Travel Time of a P-Wave Between Two Transducers

3. The first step is to position the cursor to mark the P-wave arrival on the upper waveform. (The arrival of the direct P-wave at a transducer is the point at which the voltage first rises above the horizontal line—the "zero" level of voltage). To position the cursor on the upper graph, use the **{Ll}** key to move the cursor several digital points to the left, and then move it slowly back to the right, using the **{:;}** key. As the cursor traverses the flat portion of the waveform, the voltage oscillates between -0.0002 and -0.0001 volts (this is low level "noise" in the system) until the rising portion of the waveform is reached. The first point at which the voltage increases significantly is **87.5/0.0001v**, indicating that at 87.5 microseconds after the trigger point the voltage suddenly increased to 0.0001v. Leave the cursor at this point, which marks the P-wave arrival at the first transducer.

4. The second step is to position the second cursor to mark the P-wave arrival on the lower waveform. Follow the procedure outlined above, using the **{<,}** key to move the cursor to the left and the **{>.}** key to move it to the right. On the flat portion of the waveform leading up to the wave arrival, the voltage remains steady at 0.0006v. The first point at which it rises significantly is **157.5/0.0007v**. Leave the cursor at this point. The **Cursor to Cursor** box in the upper right of the graph indicates that the elapsed time between the P-wave arrival at the two transducers is 157.5 – 87.5 = 70.0µs.

5. Click **WaveSpd from P-Wave** to calculate the P-wave speed [Keyboard: press "**Alt+P**"]. A text box appears, showing two P-wave speeds. The speed of 4286 m/s, given for "Beams and Columns", is the true P-wave speed, and the second value, 4114 m/s, is the "apparent P-wave speed in a plate" (0.96 times the true P-wave speed) used for all tests on plate structures (see *Sansalone and Streett*, pp. 51-52).

6. Records 3 and 4 in the file that has been opened, **c:\ImpactDemo\TestFile.dat**, show additional measurements of P-wave speed in concrete. Follow the instructions given above to determine the P-wave speed from these records. The plate P-wave speeds determined from these records should be around 4100 m/s.

P-Wave Speed From Impact-Echo Tests on a Plate of Known Thickness.

The fundamental equation of impact-echo is **d =** b**Cp/(2f)** where b is a "shape factor" that depends on the geometry of the structure being tested, **d** is a characteristic dimension, **Cp** is the P-wave speed, and **f** is frequency. For plate structures b = 0.96,[7] and the key frequency—called the "thickness frequency"—is the vibration frequency induced by multiple P-wave reflections between the top and bottom surfaces. If the thickness **d** of a solid concrete plate is known, and

[7] In the early work on impact-echo, the existence of the "shape factor" b was unknown, and the quantity 0.96**Cp** was used as the wave speed for plates. It is sometimes called "the apparent P-wave speed in a plate", or **Cp,plate**.

the thickness frequency **f** is measured in an impact-echo test, the wave speed **Cp** can be calculated. The following steps illustrate this procedure.

7. Open record 5 in the file **c:\ImpactDemo\TestFile.dat**. It shows the results of an impact-echo test on a slab that is known to be 240mm thick. A value of 4000 m/s has been used as a first estimate of the wave speed. If this were the correct wave speed, the thickness frequency would be 8.3 kHz (shown in the text box in upper right and marked by the position of vertical blue line on spectrum). However, the results of the impact-echo test show that the measured thickness frequency is 7.8 kHz, the frequency of the main peak in the spectrum (the lower graph).

8. To calculate the correct wave speed, click the **6 Thickness Frequency** text box in the upper right of the screen [Keyboard: press "**Alt+6**"], enter the observed frequency of 7.8 kHz, and press **Enter** to accept this value into the computer memory.

9. In the **Recalculate Parameters** box that appears (Figure IV-6) select **P-Wave Speed** as the parameter to calculate, and click **Calculate**. This screen disappears and the correct P-wave speed of 3744 m/s appears in the text box at the upper right of the screen displaying record 5. The blue "thickness frequency" line on the spectrum now coincides with the observed peak at 7.8 kHz.

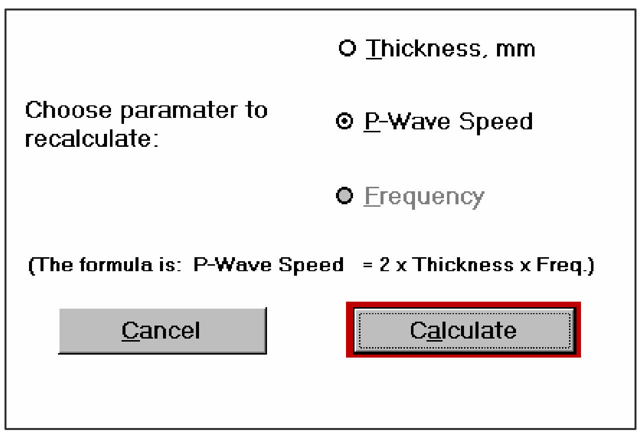


Figure IV-6. The **Recalculate Parameters** box.

The known thickness of 240mm and the observed frequency of 7.8 kHz have been used to calculate the correct wave speed of 3744 m/s. This is the "apparent P-wave speed in a plate". The true P-wave speed is this value divided by 0.96, or 3900 m/s (see *Sansalone and Streett,* pp. 51-52).

Measuring Plate Thickness When the P-Wave Speed is Known

After the wave speed has been measured, impact-echo tests can be used to determine the thickness of concrete plates. This is illustrated using impact-echo records 6 to 8 from the file **c:\ImpactDemo\TestFile.dat**. These records are from tests to determine the thickness of a concrete tunnel wall. The wave speed was measured independently using two transducers on the surface, and found to be 3996 m/s (this is the value of the "apparent P-wave speed in a plate").

Impact-echo tests were then carried out to measure the thickness, using a grid of points on the wall. A value of 400mm was used as a first estimate of thickness for each test.

10. Use the **Next Record** and/or **Prev. Record** commands to open record 6 in the file **c:\ImpactDemo\TestFile.dat**. An alternate method is to click the **Number** text box in the lower left, enter "**6**" and press the **Enter** key. The test results for record 6 (record name J2) show that a wave speed of 3996 m/s and a thickness of 400mm give an expected "thickness frequency" of 5.0 kHz. These three numbers appear in the three text boxes labeled **Thickness, Wave Speed**, and **6 Thickness Frequency**, at the upper right of the screen. The light blue vertical line on the spectrum marks the expected "thickness frequency" of 5.0 kHz. The presence of a single dominant frequency of 6.3 kHz in this test record indicates that the true thickness is less than the estimated thickness of 400mm.

11. To calculate the true thickness using the known wave speed of 3996 m/s and the observed thickness frequency of 6.3 kHz, click the **6 Thickness Frequency** text box in the upper right [Keyboard: press "**Alt+6**"], enter "**6.3**", and press **Enter**. The **Recalculate Parameters** screen appears (see Figure IV-6).

12. Click the **Thickness** option box [Keyboard: press "**Alt+T**"] to select thickness as the parameter to recalculate, and click **Calculate** [Keyboard: press "**Alt+a**"]. The **Recalculate Parameters** screen disappears, and the calculated thickness of 317mm appears in the **Thickness** text box in the upper right of the screen. At the same time the light blue thickness frequency line on the spectrum is placed at the frequency of the dominant peak, 6.3 kHz. The thickness of the plate at point J2 has been found to be 317mm.

13. Open records 7 and 8 in the current file (**c:\ImpactDemo\TestFile.dat**) and determine the wall thickness. These are records from the same plate described in record 6. For record 7 (Record Name K2) the thickness frequency is 5.4 kHz and the correct thickness is 370mm. For record 8 (Record Name L3), the thickness frequency is 11.2 kHz and the correct thickness is 178mm.

14. Click **Main Menu** to return to the **Main Menu** screen, and click **Exit** to close the program.

This completes Section IV of this tutorial, covering the use of impact-echo to measure P-wave speed and plate thickness. Repeat the action steps in this section until you are thoroughly familiar with the topics covered.

The next section describes how impact-echo is used to locate and identify cracks and voids in plate structures.

Section V: Detecting Cracks and Voids in Plates

Introduction

The impact of a steel sphere on a solid concrete plate causes multiple reflections of P-waves between the top and bottom surfaces, characterized by a resonant frequency that is a function of P-wave speed and plate thickness. Patterns of stress wave propagation and reflection and the resulting frequencies are changed by the presence of flaws. These changes appear in the waveforms and spectra obtained from impact-echo tests, and they provide both qualitative and quantitative information about the flaws. This section focuses on behavior associated with cracks and voids in plates, including the special case of a shallow crack or delamination, and the response of plates containing unconsolidated concrete (honeycombing). Although the discussion is focused on plate structures, the interaction of stress waves with flaws and the resulting changes in the waveform and spectrum can be generalized to any geometry. For a more detailed discussion of these topics, see *Sansalone and Streett*, Chapters 9-12.

Cracks and Voids

A crack or void within a concrete structure forms a concrete/air interface. Laboratory experiments have shown that cracks with a minimum width (crack opening) of about 0.08mm (0.003 inches) cause almost total reflection of a P-wave. The responses from cracks and voids are similar, because stress waves are reflected from the first concrete/air interface encountered. Thus a crack at a depth **d** will give the same response as a void whose upper surface (nearest to the impact surface) is at the same depth (Figure V-1).

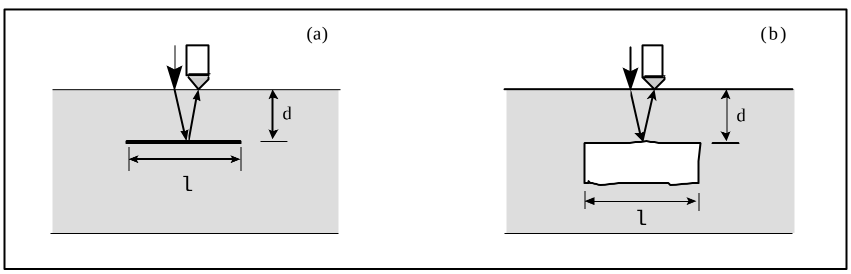


Figure V-1. A crack at depth **d** gives the same response as a void at that depth.

Determine the Solid Response of the Plate Structure

When tests are carried out to locate flaws in a plate structure, the first step is to determine the response of the solid structure. This is accomplished by performing tests in a region where the structure is known to be solid. If the thickness and wave speed are known, the thickness frequency can be calculated, and tests can be performed until a solid response is obtained. In this section test records for a 240mm thick plate structure will be examined.

1. Open the existing data file **c:\ImpactDemo\TestFile.dat**, and open record. Record 9 shows the results of a test on a solid portion of a 240mm thick plate, using an estimated wave speed of 4000 m/s. The expected thickness frequency for this wave speed is 8.3 kHz (text box at upper right of screen). However, the observed frequency (the main peak in the spectrum) is 7.8 kHz. The presence of a single dominant peak, with a frequency near the expected thickness frequency, indicates that this is a solid response. The observed thickness frequency of 7.8 kHz can be used to calculate the correct wave speed.

2. Click the **6 Thickness Frequency** text box in the upper right of the screen, enter the observed frequency of 7.8 kHz, and press **Enter**. In the box that appears, select **P-Wave Speed** as the parameter to calculate, and click **Calculate**. The correct plate P-wave speed of 3744 m/s appears in the box at the upper right, and the vertical blue line that marks the thickness frequency on the spectrum is moved to 7.8 kHz.

   Analysis and Interpretation. To understand the relationship between the 7.8 kHz peak in the spectrum and the periodic structure of the waveform, use the **{Kk}** and **{"'}** keys to place the active waveform cursor on the first positive peak after the R-wave. The label on the cursor reads 258, the elapsed time in µs after the trigger point. Double click on the active cursor or click **Change Cursor** [Keyboard: press "**Alt+C**"] to make the second cursor active, and use the **{Kk}** and **{:;}** keys to move that cursor to the second positive peak, at 388 µs after the trigger point. The time separation between the cursors—130 µs as shown in the box at the upper right of the graph—is the approximate period of the waveform. The frequency is the reciprocal of the period: **f** = 1/0.000130 = 7692 Hz or 7.7 kHz. This is close to the frequency of the main peak in the spectrum, 7.8 kHz. Try measuring the period using other adjacent peaks in the waveform. The resulting frequencies will vary slightly, but the average will be about 7.8 kHz.

Flaws of Wide Lateral Extent

3. Open record 10 in the current data file, **c:\ImpactDemo\TestFile.dat**. This is the result of a test on the same plate described in record 9, in a region where cracks are suspected.

4. To compare the spectrum of this record with that of the solid structure in record 9, click the text box at the right of the **Compare** button at the bottom of the screen [Keyboard: press the **tab** key repeatedly until the text box is highlighted], enter "**9**" and click **Compare** or press the **Enter** key. The spectrum from record 9 is overlaid on the current spectrum as a dashed green line. The response in record 10 is dramatically different from the solid response of record 9, indicating the presence of a flaw.

   Analysis and Interpretation. Place the spectrum cursor on the main peak at 12.2 kHz. The indicated depth is 153mm, shown in the upper right of the spectrum and also by the horizontal cursor in the thickness box at the right of the screen. The existence of a single dominant peak in the spectrum indicates that the response is due to multiple P-wave reflections in a 153mm thick layer above a wide crack.

   Place the waveform cursors on the third and fourth peaks after the R-wave (390 and 472 µs after the trigger point). This gives an approximate period of 82 µs, corresponding to a frequency of 12.2 kHz, in agreement with the frequency of the main peak in the spectrum. Similar frequency values are obtained from the period measured between adjacent peaks near the end of the waveform. The vertical scale of the waveform can be set to a lower voltage (0.2 volts, for example) to make the structure of the latter part of the waveform easier to see.

The difference between the solid response and the response when a crack of wide lateral extent is present is illustrated in Figure V-2.

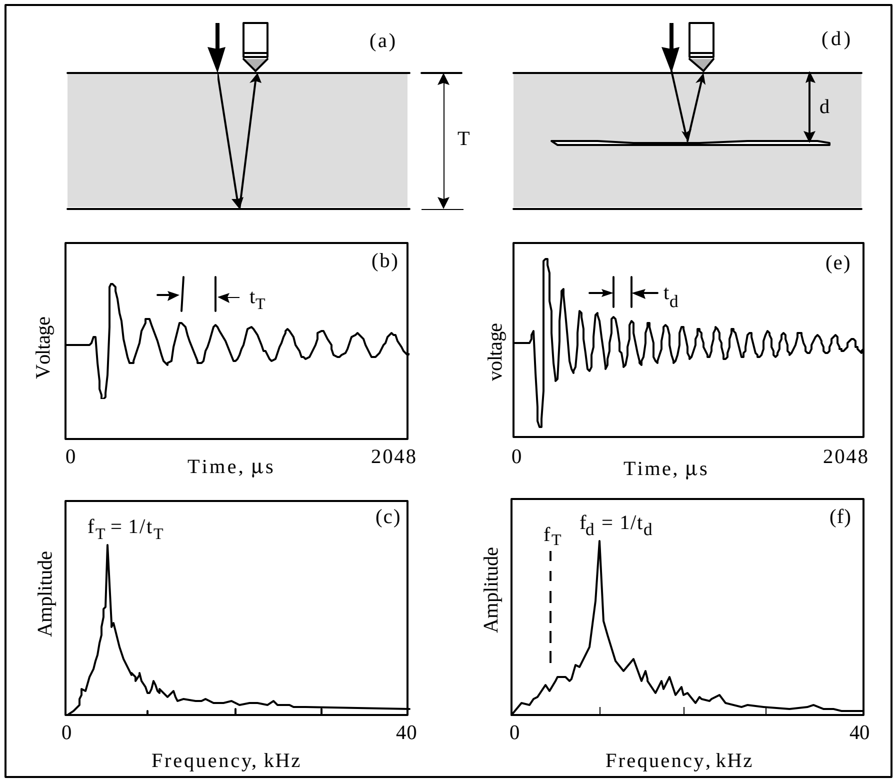


Figure V-2. Comparison of the solid response (left) with the response from a region with a crack of wide lateral extent.

Flaws of Limited Lateral Extent

When the lateral dimensions of a crack are comparable to its depth, stress waves are both reflected from the crack and diffracted around it. As a result, multiple P-wave reflections occur both within the layer above the crack and across the full thickness. However the full thickness frequency is lower than that of the solid plate because of the reduced stiffness in the vicinity of the crack and because the P-waves must travel a longer path around the crack to reach the bottom surface.

5. Open record 11 in the file **c:\ImpactDemo\TestFile.dat**. This shows the results of a test on the same 240mm thick plate described in the previous two records.

6. Click the **Compare** text box at the bottom of the screen, enter "**9**" and press **Enter** to overlay the solid response from record 9. The spectrum for record 11 is very different from that of the solid response, again indicating the presence of a flaw.

   Analysis and Interpretation. There are two peaks of about equal amplitude in the spectrum, one at 13.2 kHz and one at 3.9 kHz. Use the mouse or the **{Mm}** and **{?/}** keys to move the cursor between these two peaks. When the cursor is at the 13.2 kHz peak, the indicated depth is 142mm. This is the depth of the flaw. When the cursor is at the 3.9 kHz peak, the

depth indicated in the box on the graph (in red letters) is 479mm and the caption on the depth box at the right reads “Cursor out of range”. The 3.9 kHz peak is a “displaced thickness frequency”—that is, the solid thickness frequency of 7.8 kHz has been displaced to a lower frequency (3.9 kHz) because of the reduced stiffness of the slab in the vicinity of a flaw, and because of the increased path length taken by the stress waves that travel around the flaw to reach the bottom of the slab. This is a common pattern in impact-echo testing. ***The presence of a significant peak in the spectrum at a frequency below the thickness frequency for the solid plate is a certain indication of a flaw.*** This is illustrated schematically in Figure V-3.

When the depth of the flaw is greater than about 10 cm (4 inches) the response from multiple P-wave reflections within the layer above the flaw is relatively strong (the 13.2 kHz peak in record 11). If the depth of the flaw is less than 10 cm, flexural vibrations in the thin layer are often excited, and the response is dramatically different. This case is treated in the next paragraph.

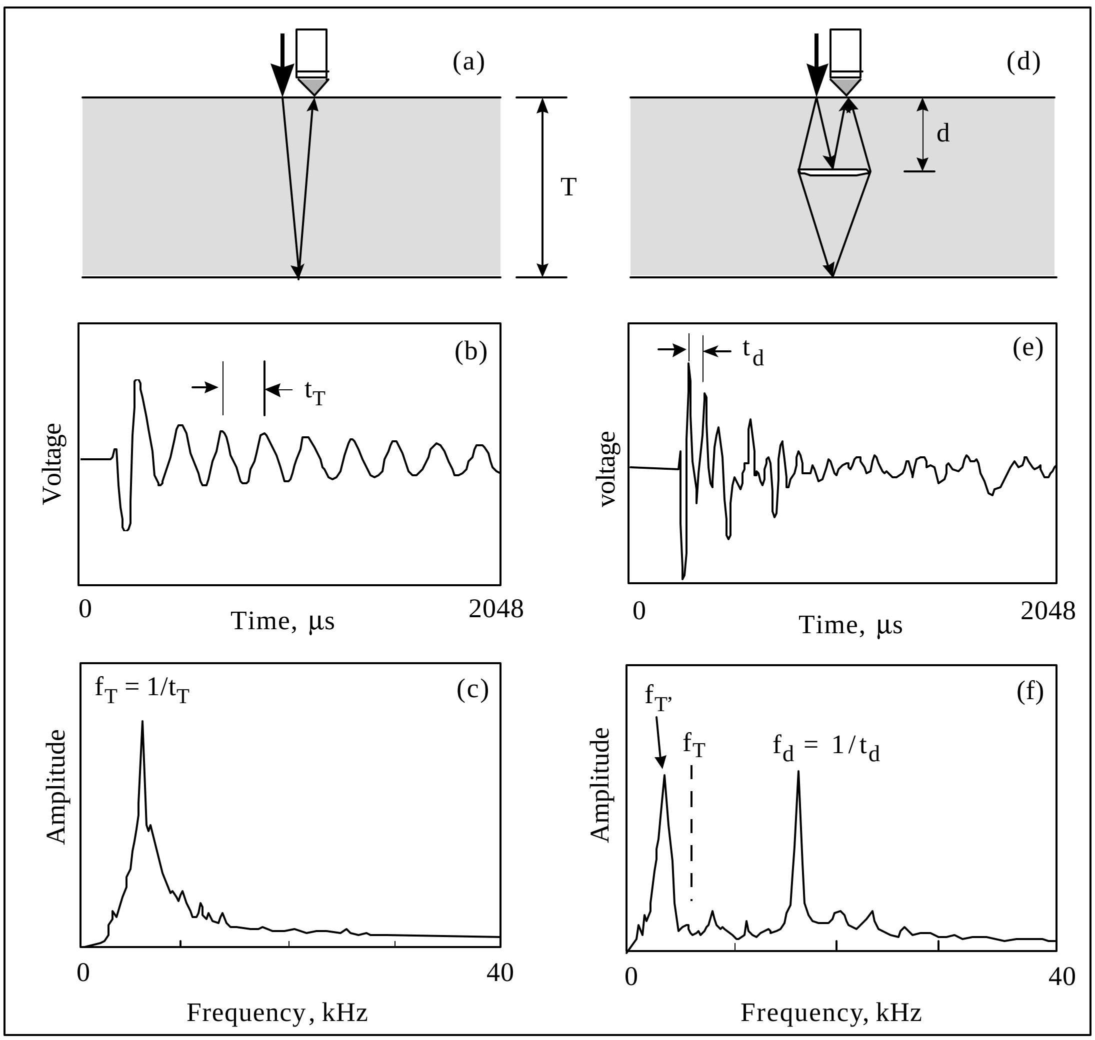


Figure V-3. Comparison of solid response (left) with response in the vicinity of a flaw of limited lateral extent.

Shallow Flaws and Delaminations: A Special Case

If a crack is less than about 100mm (4 inches) below the surface of a concrete structure, an impact excites flexural vibrations in the thin layer. (This situation is frequently encountered on concrete bridge decks, for example, where widespread cracking—called delamination—occurs at shallow depths due to corrosion in the reinforcing steel.) The resulting signal includes a large-amplitude, low-frequency component due to the flexural vibration. Flexural vibrations are similar to the vibrations in a drum, and because the resulting surface displacements are far larger than those caused by P-wave arrivals they dominate the signal. The higher-frequency component due to multiple P-wave reflections across the thin layer is weak by comparison, and sometimes difficult to detect. This phenomenon is discussed in Chapter 10 of *Sansalone and Streett* (pp. 99-114).

A schematic representation of the effects of flexural vibrations in thin layers is shown in Figure V-4. Flexural vibrations, shown schematically in (a), have low frequencies (typically 2 – 6 kHz) and very large amplitudes compared to surface displacements caused by the arrival of reflected P-waves, shown schematically in (c). Figures (b) and (d) show the corresponding contributions to the spectrum: flexural vibrations produce a high-amplitude, low-frequency signal that dominates the waveform and spectrum, while the peak resulting from P-wave reflections has a higher frequency and lower amplitude, and is sometimes too small to be seen. There are two methods for amplifying this high frequency peak: (1) using a smaller impactor and (2) digital filtering. These are discussed below.

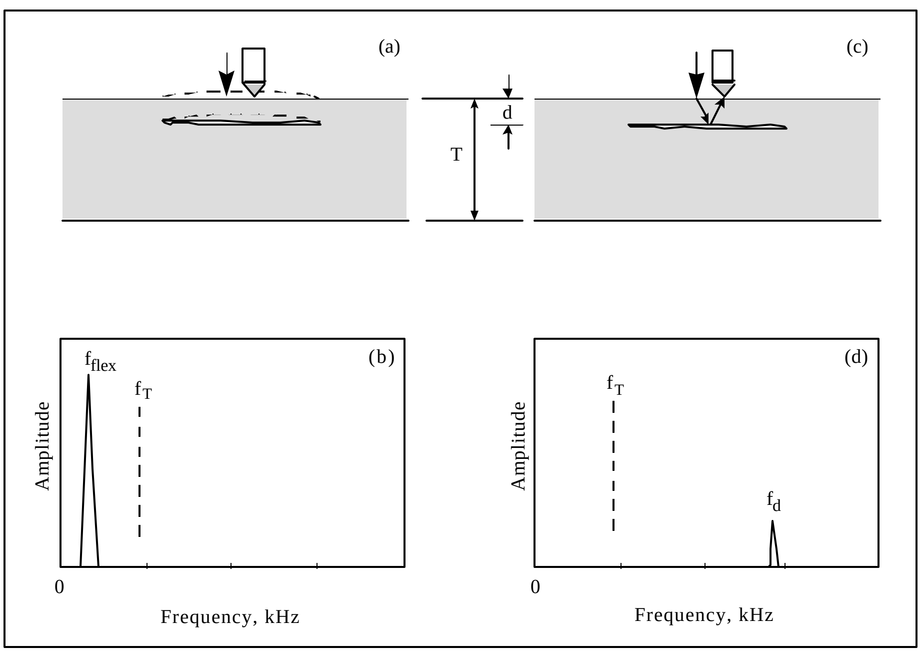


Figure V-4. The principal components of the response produced by impact on the surface of a concrete slab containing a shallow delamination: (a) flexural mode, and (c) thickness mode. The contributions to the spectrum are shown in (b) and (d).

7. Open record 12 in the file **c:\ImpactDemo\TestFile.dat**. This shows the results of a test on the same 240mm thick plate examined in the preceding paragraphs.

Recognizing Flexural Vibrations. In the waveform, there is a low frequency component with a large amplitude that decays very slowly. To confirm the slow decay, click the **3 H. Scale** text box at the lower right of the waveform graph, enter "**2048**" in place of 1024, and press **Enter**. The result is a plot of the waveform over the entire range of 2048 recorded data points (about 4 milliseconds). The decay in the magnitude of flexural vibrations over this period is small. To emphasize this point, click **Prev. Record** [Keyboard: press "**Alt+V**"], and compare the waveform in record 11 to that in record 12. To return to record 12, click **Next Record** [Keyboard: press "**Alt+X**"]. These two records have comparable vertical scales, so the amplitudes can be directly compared. Notice how rapidly the amplitude of the P-wave reflections in record 11 decays, compared to that of the flexural vibrations in record 12. The presence in the waveform of a high-amplitude, low-frequency, slowly decaying component is the hallmark of flexural vibrations in a thin or delaminated layer. It is apparent from the shape of the beginning of the waveform that a smaller-amplitude, higher-frequency component is present, indicated by the closely spaced peaks superimposed on the low frequency component. The spectrum is dominated by large peak at 4.9 kHz, although there is a hint of a smaller peak around 20 kHz.

8. Click the **Compare** text box at the bottom of the screen, enter "**9**" and press **Enter**, to overlay the solid response on the spectrum. The current record exhibits a strong, low-frequency peak below the thickness frequency—a certain indication of a flaw. The absence of strong peaks in the spectrum above that frequency suggests that a smaller impactor might be needed to generate stress waves covering a broader range of frequencies.

Using the R-Wave to Determine Contact Time and Frequency Content

9. The maximum useful frequency in an impact-echo test can be determined from the contact time—the length of time the sphere is in contact with the concrete surface during an impact. With record 12 as the open record, click the **Contact Time** command button (beneath the waveform) to expand the leading part of the waveform for measurement of the contact time. The screen shown in Figure V-5 appears.

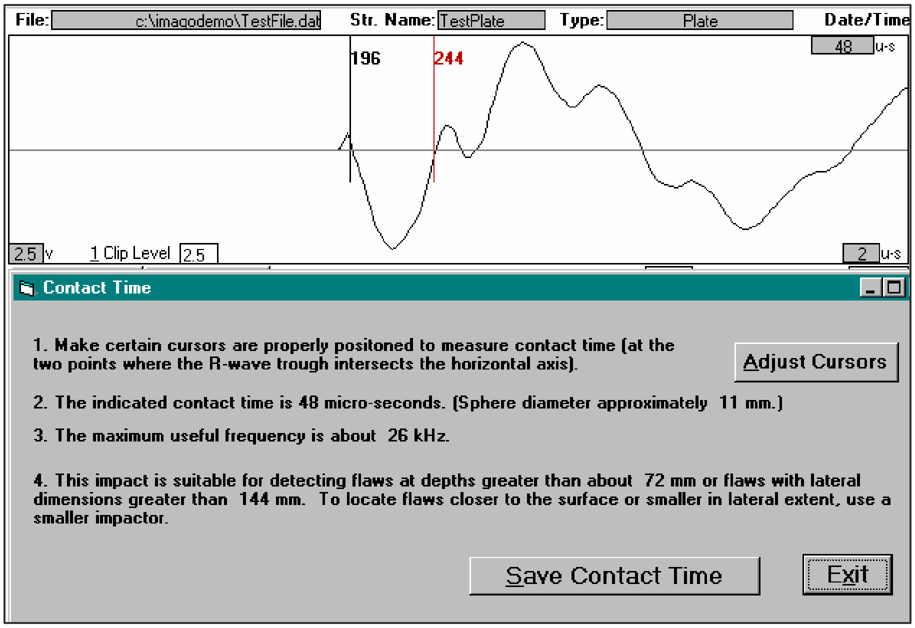


Figure V-5. The **Contact Time** screen with the R-wave drawn on an expanded scale.

10. The two cursors should be positioned at the points where the R-wave trough crosses the zero voltage line (the horizontal line). The width of the R-wave between these two points is equal to the contact time, the length of time the impacting sphere is in contact with the concrete surface during the impact. If necessary, click **Adjust Cursors** and use the mouse or keyboard to properly position the cursors, and click **Contact Time** again. The text on the **Contact Time** screen gives the measured contact time (it is about 48 µs in this case), the approximate diameter of the impacting sphere (11mm), the maximum useful frequency in the signal (26 kHz), and information about sizes and depths of flaws that can be detected. (For more information, see Table 15, p. 302 of *Sansalone and Streett*.) Click **Save Contact time** to save the measured contact time a permanent part of this test record. This will cause the contact time to appear at the bottom of the waveform graph when the record is opened, as shown for record 12. Click **Exit** to return to the **Examine Test Data** screen without saving the contact time.

    Use the R-wave to determine the frequency content of the impact. The surface wave or R-wave, which appears as a deep trough at the beginning of the waveform, is a mirror image of the force-time function of the impact, and it provides useful information about the distribution of amplitudes and frequencies in the resulting stress waves. (See *Sansalone and Streett*, Chapter 3.) Place the active waveform cursor at the right side of the R-wave (elapsed time 244 µs) and click **Cut Waveform** to set equal to zero that portion of the waveform to the right of the cursor. The result is a spectrum showing the distribution of amplitudes and frequencies produced by the impact (Figure V-6).

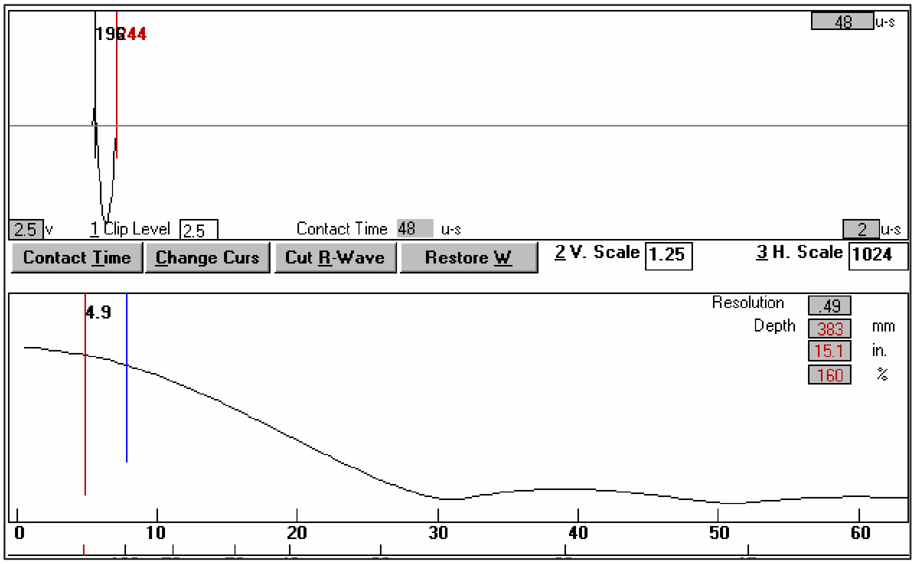


Figure V-6. The R-wave (upper graph) and associated spectrum (lower graph).

In the spectrum the height of the curve at any point on the horizontal axis is a measure of the relative amount of energy in the stress waves at that frequency. The graph shows that there is very little energy at frequencies above about 26 kHz, and that the energy level is relatively low even at 20 kHz. This explains, in part, why the peak near 20 kHz in record 12 is small, and suggests that if there were more energy in that part of the spectrum it would be larger. A smaller impactor, which produces stress waves with a broader range of frequencies, might be effective in clarifying the structure in the spectrum around 20 kHz.

10. Click **Restore W** to restore the full waveform (record 12). Place the waveform cursors on two adjacent large peaks in the waveform—at 738 and 948 µs, for example. The approximate period of the low-frequency component of the waveform is 210 µs, which corresponds to a frequency of about 4.8 kHz—the approximate frequency of the large peak in the spectrum.

11. Place the cursors on adjacent secondary peaks superimposed on the low-frequency signal, at 338 and 390 µs, for example (Figure V-7). (The horizontal scale has been set at 512.)

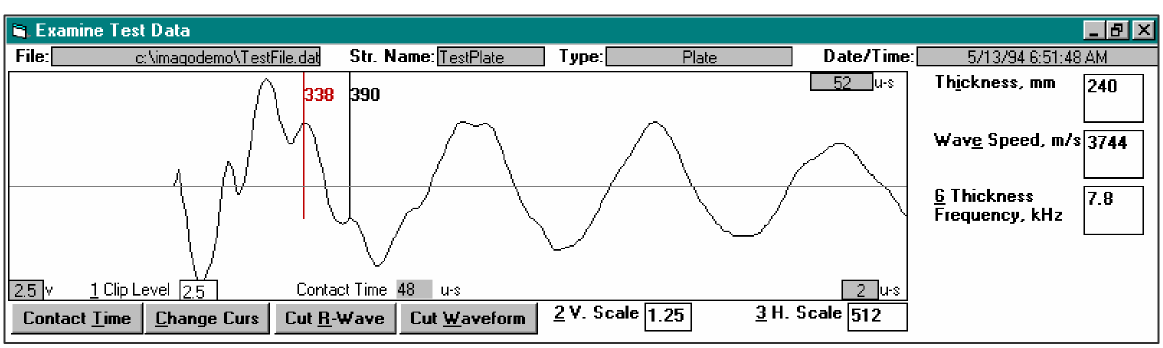


Figure V-7. The waveform in record 12, with cursors on two adjacent peaks of the high-frequency component.

The period is 52 μs (shown in the box at the upper right of the graph), corresponding to a frequency of about 19 kHz. This is a good indication that there is a frequency component near 20 kHz, and that the subdued peak in that vicinity of the spectrum represents the thickness frequency of the thin layer above the flaw. Two methods are available to further clarify this point: (1) using a smaller impactor, and (2) removing low frequencies by digital filtering.

Using a Smaller Impactor to Amplify High Frequency Components

12. Open record 13 in the file **c:\ImpactDemo\TestFile**. The results on the screen are from an impact-echo test at the same point as the previous record, but with a smaller impactor. There is now a significant peak at 19 kHz, which confirms the suspicion that this is the thickness frequency of the thin layer. The indicated thickness of this layer is 98mm, a thickness likely to exhibit flexural vibrations. Careful measurement of the contact time (see step 9 above) shows that it is about 14 μs. This indicates that a sphere of approximately 3mm diameter was used in this test, producing a maximum useful frequency of 89 kHz.

    Choosing the Right Impactor. In routine testing it is usually best to start with a large impactor (10mm diameter or larger) and use a smaller impactor if it is necessary to amplify or "bring up" features that are associated with frequencies of about 20 kHz and higher. A 3mm diameter impactor (the smallest practical size is 1/8-inch or about 1.5mm in diameter) produces stress waves with useful frequencies up to almost 90 kHz, and wavelengths as small as 0.04 m. At the high end of this frequency range, the stress waves begin to be scattered and reflected by the natural inhomogeneous regions in concrete, such as small air inclusions, mortar/aggregate interfaces, etc., with the result that there is more "noise" in the waveform and spectrum. This is apparent in record 13, a test performed with a 3mm diameter impacting sphere.

Removing Low Frequencies by Digital Filtering

The dominant low frequency peaks in records 12 and 13 of the file **c:\ImpactDemo\TestFile.dat**, resulting from flexural vibrations of the thin layer above a crack or delamination. Their presence is a certain indication that a flaw is present, but in the case of record 12, the low frequency peak so dominates the spectrum that the other important peak at about 19 kHz has a relatively small amplitude and is easily overlooked. In order to amplify a higher-frequency peak in the waveform it is sometimes useful to remove low-frequency components by digital filtering. This is accomplished through a numerical process applied to the waveform. In the **ImpactDemo** program this method can be used to remove frequencies below a specific value (the frequency marked by the position of the cursor) up to a maximum of 20 kHz.

Digital filtering should be used with caution. In general no useful information will be lost if the frequencies removed by filtering are below the thickness frequency. However, if frequencies above that level are removed, important information about the structure can be lost.

13. Open record 12 in the file **c:\ImpactDemo\TestFile.dat**, and place the spectrum cursor at 12.2 kHz, about midway between the 4.9 kHz peak and the subdued peak near 19 kHz. Click

the **Filter Low Freq** command in the lower right of the screen. Click **Yes** in the message box that appears, or press **Enter**. The screen shown in Figure V-8 appears.

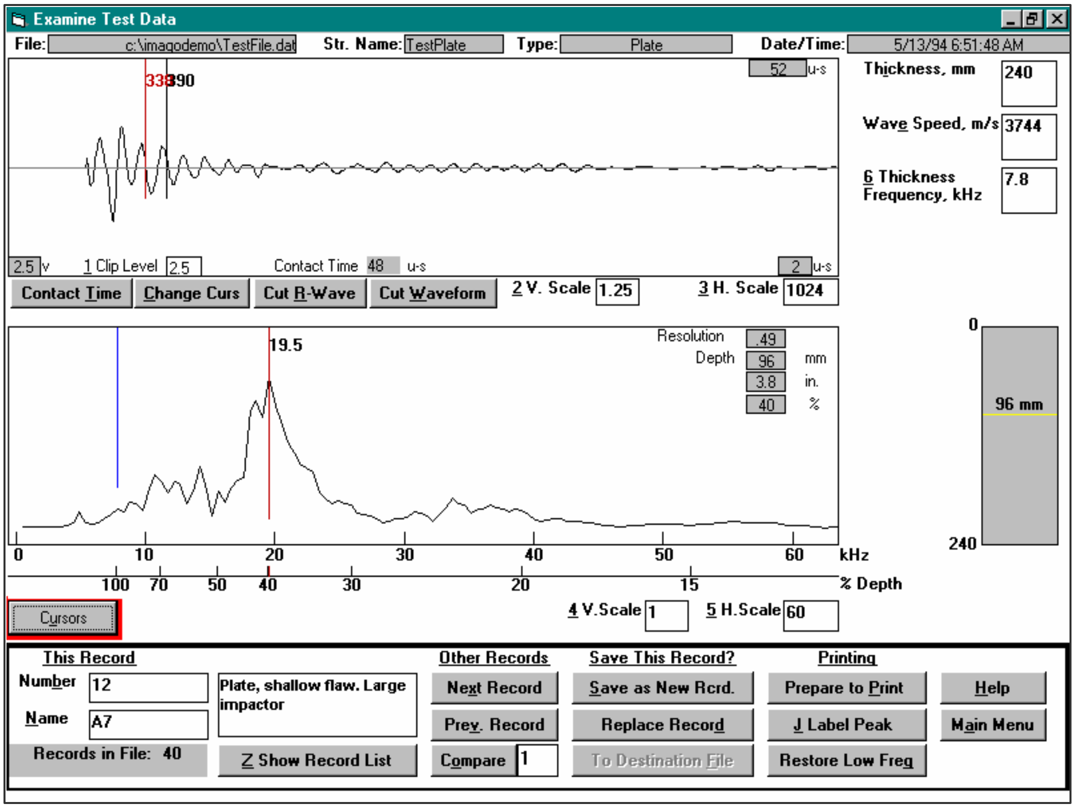


Figure V-8. Record 12 with frequencies below 12 kHz removed by digital filtering.

Note the dramatic change in both the waveform and spectrum. The large-amplitude, low-frequency component has been removed, leaving a 19.5 kHz component—the thickness frequency of the thin layer—as the dominant component. This component persists for a relatively long time in the waveform, even though it was hardly visible beyond the second or third major peak before the low-frequency component was removed. Click **Restore Low Freq** to restore the low-frequency component. To gain an understanding of the effects of digital filtering, click this button several times, and observe the changes in both the waveform and spectrum.

14. Open record 13. Place the spectrum cursor at about 12.2 kHz and click **Filter Low Freq**. The low-frequency component is removed from the signal, leaving a peak at 19 kHz (depth 98mm) as the dominant peak. The additional high-frequency structure in the spectrum is the response to the high-frequency stress waves produced by a 3mm diameter impactor.

15. Open record 11, the result of a test over a relatively deep flaw, where the low-frequency peak represents a displaced thickness frequency (step 6 above). Place the spectrum cursor midway between the two main peaks (3.9 and 13.2 kHz) and click **Filter Low Freq**, to remove the lower frequency peak. Removal of the strong low-frequency component changes the waveform from a relatively complex structure to one that is dominated by a single frequency, and has some resemblance to a decaying sine wave. The single dominant peak in the

spectrum, at 13.2 kHz, is associated with multiple P-wave reflections within the concrete layer above the crack. The depth of the crack is calculated to be 142mm.

Unconsolidated Concrete

A region of unconsolidated concrete typically consists of large numbers of small, interconnected voids, commonly referred to as "honeycombing". Such areas include many small concrete/air interfaces over a range of depths, and often they do not have a well-defined external boundary. The interaction of P-waves with regions of honeycombing is discussed in Chapter 11 of *Sansalone and Streett* (pp.115-122). The usual response of a honeycombed region to an impact-echo test includes a "displaced thickness frequency" – that is, a strong peak at a frequency below that of the solid plate – and one or more additional peaks representing P-wave reflections from a range of depths within the unconsolidated region.

16. Open record 15 in the file **c:\ImpactDemo\TestFile.dat**. This record is from a test on a 240mm thick plate with a region of honeycombing at depths from about 100mm to 135mm.

    Analysis and Interpretation. The peak at 4.9 kHz is the "displaced thickness frequency" peak, displaced downward from the solid thickness frequency of 7.8 kHz. The peaks at 21.0, 17.6 and 14.6 kHz are the result of P-wave reflections from depths between about 93mm and 133mm. Some of the small peaks at higher frequencies are a result of the very large R-wave, produced by a strong impact close to the transducer. In this case it is useful to remove the R-wave before the spectrum is calculated. This is done by placing the active waveform cursor at the right of the R-wave (at about 220 μs) and clicking **Cut R-Wave** [Keyboard, press "**Alt+R**"]. The result is shown in Figure V-9. In this figure the horizontal scale on the spectrum has been changed to 30 kHz, to show more clearly the structure in the region below that level. This change is made by clicking on the **5 H. Scale** text box [Keyboard: press "**Alt+5**"], entering "**30**" and pressing the **Enter** key. The three peaks between 14.6 kHz and 21.0 kHz have been marked by placing the cursor on each one and activating the **J Label Peak** command [Keyboard: press "**Alt+J**"].

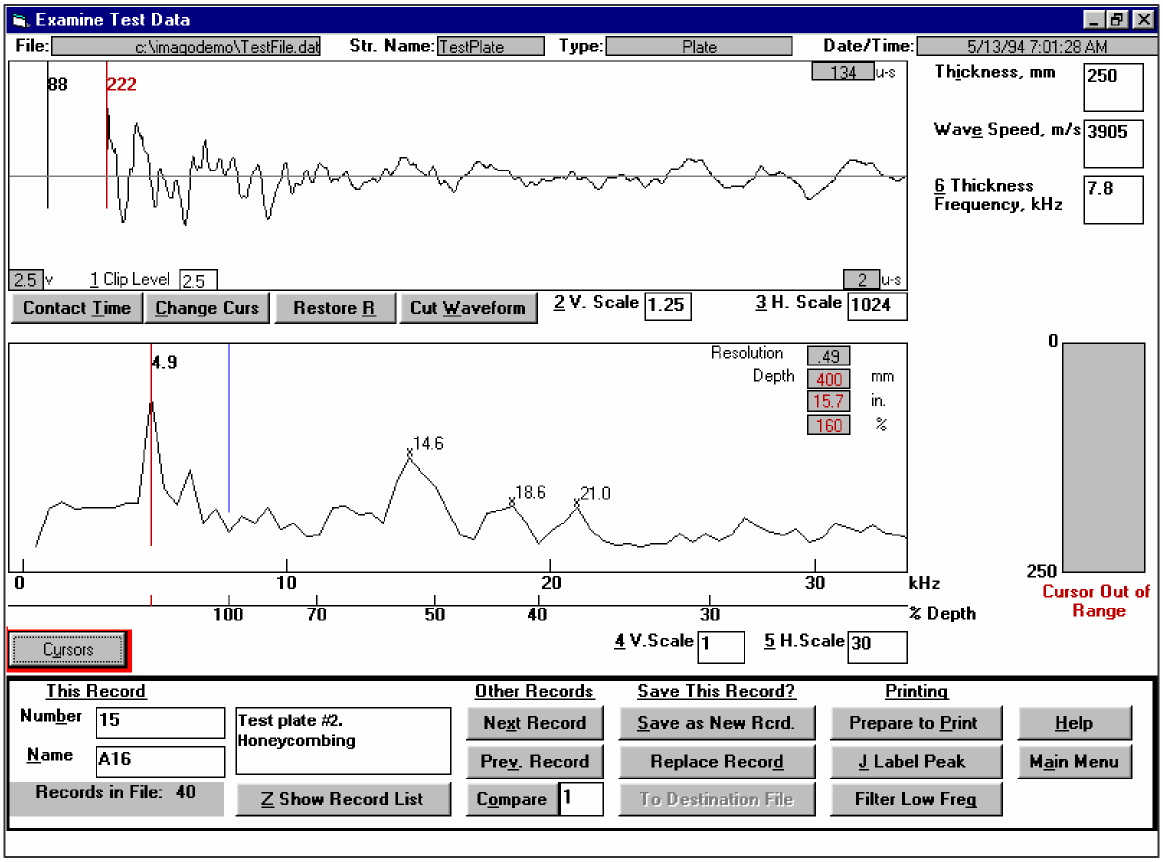


Figure V-9. Record 15 with the R-wave removed, and the horizontal scale on the spectrum changed from 60 to 30 kHz.

This completes Section V of this tutorial, covering the use of impact-echo to identify and locate cracks and voids in concrete plates. Repeat the action steps in this section until you are thoroughly familiar with the topics covered.

Section VI: Determining the Depth of Surface-Opening Cracks

Introduction

A surface-opening crack is any crack that is visible at the surface. Such cracks can be perpendicular or inclined to the surface, or curved, as shown in FigureVI-1.

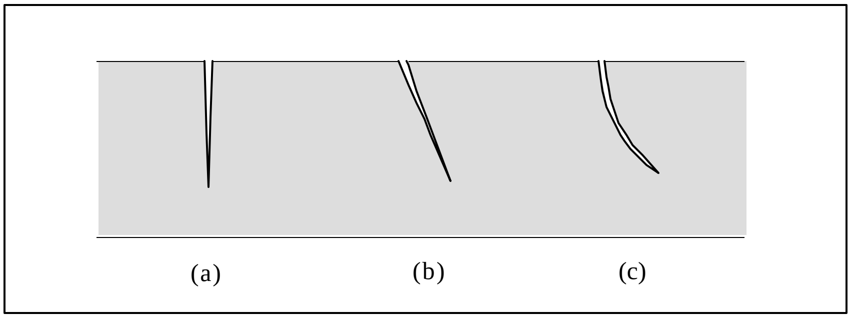


Figure VI-1. Surface-opening cracks: (a) perpendicular, (b) inclined, and (c) curved.

When stress waves are generated by an impact on the surface of concrete adjacent to a surface-opening crack, as shown in Figure VI-2(a), the pattern of wave propagation differs significantly from the pattern in solid concrete. Because the crack is a concrete/air or, in some cases, a concrete/water interface, it reflects the stress waves propagating outward from the impact point, as shown in Figure VI-2(b). If the receiving transducer is placed on the opposite side of the crack, the R-wave traveling along the surface and the spherical P- and S-waves traveling within the concrete do not reach the transducer directly. When the P-wave reaches the bottom

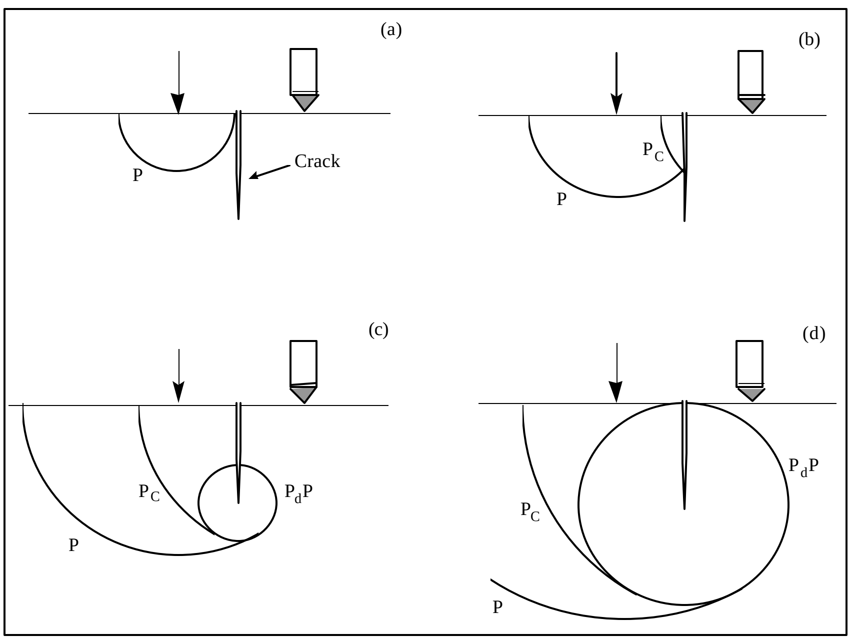


Figure VI-2. Reflection and diffraction of P-waves from a surface-opening crack: (a) initial P-wave front generated by impact, (b) P_C is the P-wave reflected from the crack, (c) and (d) P_dP is the P-wave diffracted from the bottom of the crack.

edge of the crack it produces a diffracted P-wave, labeled $\mathbf{P_dP}$ in (c) and (d), that travels outward along a cylindrical front, centered on the bottom edge of the crack. This is the first stress wave to reach the transducer.

In determining the depth of a surface-opening crack, two transducers are used, as shown in Figure VI-3. The transducer on the same side of the crack as the impact is used to determine the time of the impact, and the second transducer measures the time required for the stress wave to travel from point A (the impact point) to B (the crack tip) to C (the transducer). The two transducers and the impact point are placed on a straight line perpendicular to the line of the crack on the surface. If the wave speed and the distances $\mathbf{H_1}$, $\mathbf{H_2}$ and $\mathbf{H_3}$ are known, and the arrival times of the stress waves at the two transducers are measured, the depth of the crack can be calculated. This method, called a time-of-flight technique, is illustrated schematically in Figure VI-3, and is explained in detail in Chapter 12 of *Sansalone and Streett* (pp. 123-37). It can be used to obtain good approximations of the depths, measured perpendicular to the surface, of cracks that are perpendicular to the surface, inclined, or curved.

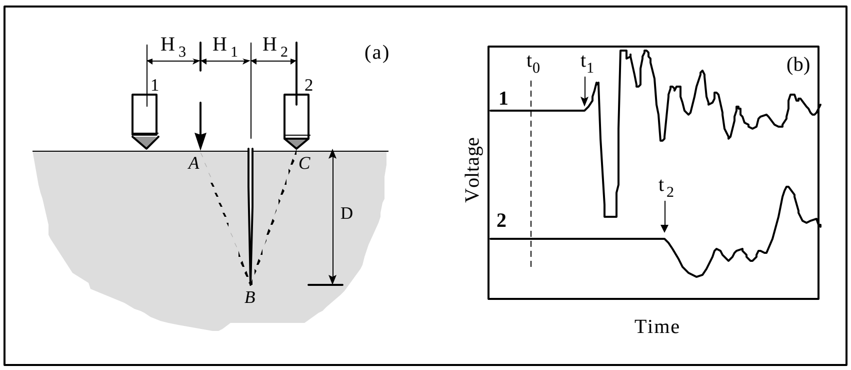


Figure VI-3. Measuring the depth of a surface-opening crack: (a) schematic of experimental test setup, and (b) sample waveforms.

The two waveforms, labeled 1 and 2, in Figure VI-3(b), are the signals from transducers 1 and 2 in the drawing at the left. The arrival of the direct P-wave, a compression wave, at transducer 1 causes an upward surface displacement and a positive voltage (time $\mathbf{t_1}$), while the diffracted wave that first reaches transducer 2 is a tension wave, which causes a ***downward displacement and a sudden voltage drop*** (time $\mathbf{t_2}$). The elapsed time between $\mathbf{t_1}$ and $\mathbf{t_2}$, the wave speed, and the known distances $\mathbf{H_1}$, $\mathbf{H_2}$ and $\mathbf{H_3}$, are used to calculate the depth **D**. In practice the operator measures the distances $\mathbf{H_1}$ **-** $\mathbf{H_3}$, performs the impact, and positions the cursors on the graph to mark $\mathbf{t_1}$ and $\mathbf{t_2}$. The software calculates the crack depth and displays it on the computer screen.

<u>Setup for Crack Depth Measurement</u>

The following action steps describe the setup and procedure for determining crack depth, and explain the interpretation of test results using data from real impact-echo tests.

1. Start the **ImpactDemo** program (see p. 14) and create and open a new data file **c:\ImpactDemo\CrakDpth.dat**, on the **c:** drive in the directory **ImpactDemo** (see pp. 16-18 or press **Help** for information on creating and opening a new file). When control is

returned to **the Main Menu** screen, click **Measure Depth of Surface Opening Crack** [Keyboard: press "**Alt+C**"] to open the **Setup for Crack Depth** screen (Figure VI-4).

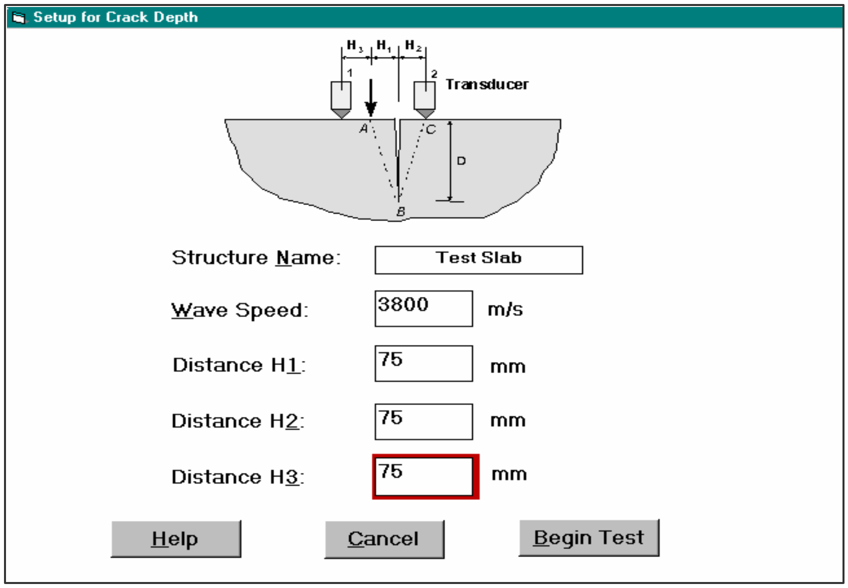


Figure VI-4. The **Setup for Crack Depth** screen.

2. Enter "**Test Slab**" as the structure name, "**3800**" as the wave speed, and "**75**" for each of the distances $\mathbf{H_1}$ - $\mathbf{H_3}$, and click **Begin Test** to open the **Measure Crack Depth** screen (Figure VI-5).

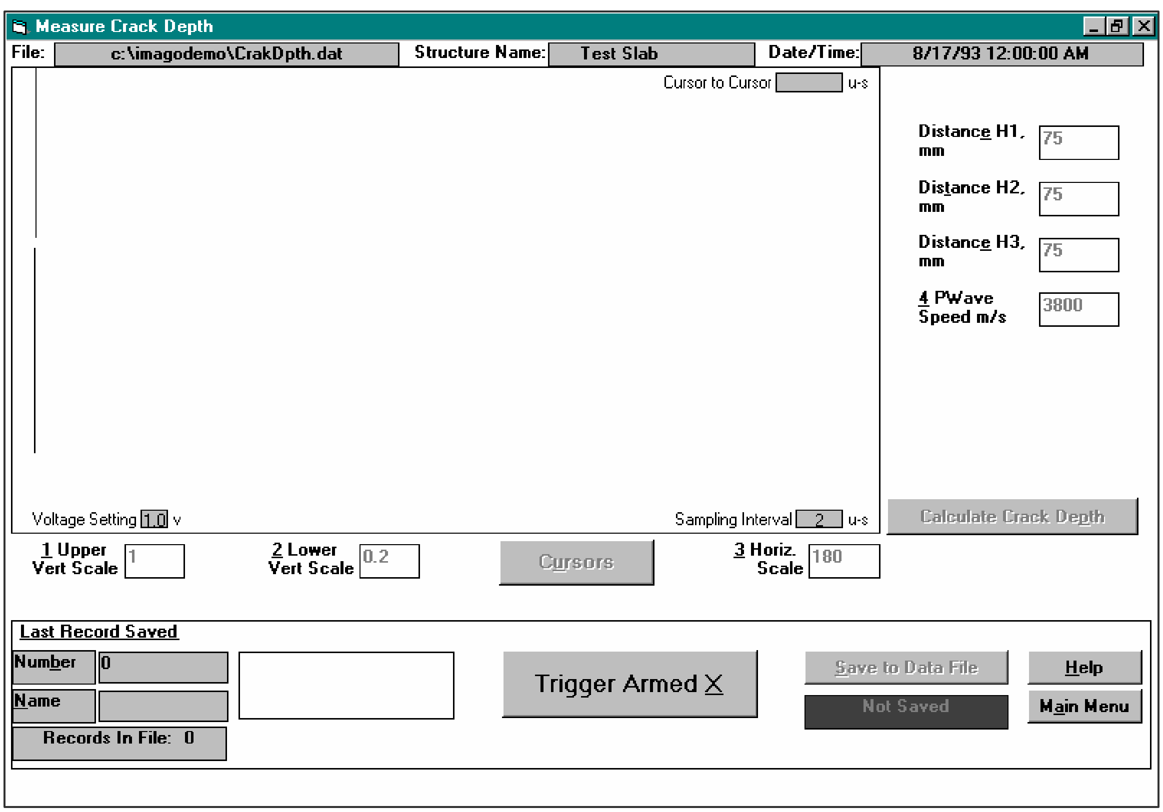


Figure VI-5. The **Measure Crack Depth** screen, ready for a test to be performed.

3. This screen contains a single graph on which the two waveforms are plotted when a test is performed. The three distances H_1 – H_3 and the wave speed appear in boxes at the upper right of the screen. After a test has been performed, these numbers can be changed by selecting one of the boxes, inserting a new number, and pressing **Enter**. Because a new file has been created and opened, the graph is blank. The green border around the **Trigger Armed X** button is flashing, indicating that the system is ready to receive the signals from a test. At this point the operator positions the transducers and the impact point as shown in figure VI-4, and performs the test.

4. To see the screen as it would appear after a test for crack depth has been performed, click **Main Menu** to return to the **Main Menu** screen. Click **Open Test Data File**, and open the existing file **c:\ImpactDemo\TestFile.dat** (press **Help** for instructions on opening an existing file). Open record 16 in this file by selecting the **Number** box at the lower left [Keyboard: press "**Alt+B**"], entering "**16**" and pressing the **Enter** key. Figure VI-6 appears on the screen, showing the results of a test to determine the depth of a surface-opening crack in a concrete slab.

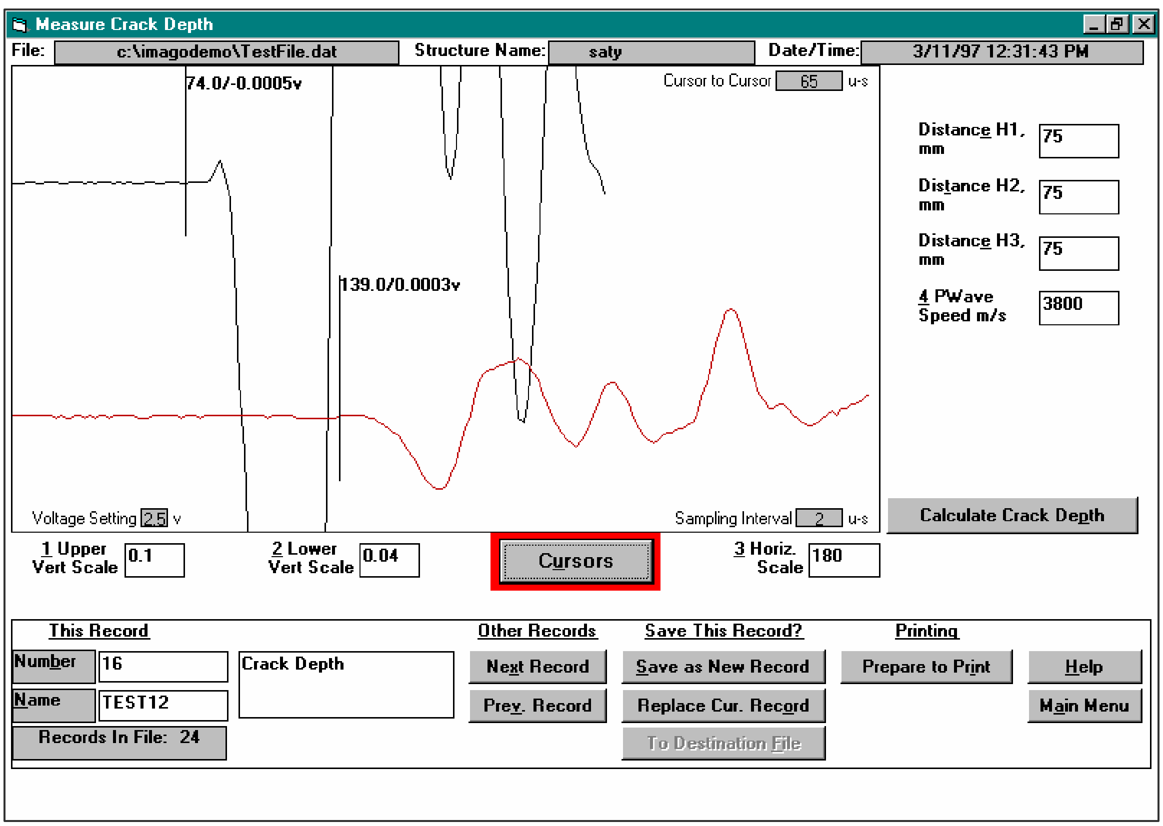


Figure VI-6. Test record for crack depth measurement. (Record 16 in file **c:\ImpactDemo\testFile.dat**).

Measuring the Elapsed Time Between P-Wave Arrivals at the Two Transducers

5. Entries in the **1 Upper Vert Scale** and **2 Lower Vert Scale** text boxes beneath the graph can be adjusted to show more clearly the structure at the beginning of each signal. The key point in the upper signal is the initial rise in voltage caused by the arrival of the direct P-wave. In the lower signal the key point is the initial voltage drop caused by the arrival of a P-wave diffracted from the crack tip (a tension wave).

   Position the Cursors. Position the cursor on the upper waveform to mark point at which the voltage first starts to rise. This is done using the mouse or the **{Ll}** and **{:;}** keys to move the cursor. The label on each cursor is in the format "**ttt.t/x.xxxx**v", where "**ttt.t**" is the time in µs after the first recorded data point and "**x.xxxx**" is the signal voltage at that instant. Start with the cursor to the left of the first voltage rise and move it slowly to the right using the **{:;}** key. In the flat portion of the waveform the voltage oscillates between –0.0005 and +0.0007 volts due to low level noise in the system. The first significant increase in voltage occurs where the label on the cursor reads **84.0/0.0019v**, indicating that at 84 µs after the first recorded data point the direct P-wave reached transducer 1. Similarly, the cursor on the lower waveform is moved using the **{<,}** and **{>.}** keys. In the "flat" or leading portion of the waveform the voltage oscillates between –0.0009 and +0.0003 volts. The first indication of a significant drop in voltage occurs when the label on the cursor reads **155.0/-0.0021v**. This indicates that at 155 µs after the first recorded data point there was a sudden drop in the voltage recorded by transducer 2, signaling the arrival of the tension wave diffracted from the bottom edge of the crack. The elapsed time between the wave arrivals at the two transducers is 71 µs, which appears in the box at the upper right of the graph.

Calculating the Crack Depth

6. With the two cursors positioned as described in the preceding paragraph, click the **Calculate Crack Depth** button at the right of the graph [Keyboard: press "**Alt+P**"]. A message box appears on the screen, indicating that the crack depth is 155mm, or 6.1 inches.

7. The next two records in the open file, records 17 and 18, are also crack depth measurements. In record 17, the upper and lower cursors are positioned at **72.0/0.0011v** and **95.0/-0.0025v**, respectively, and the crack depth is found to be 31mm, or 1.2 inches. In record 18 the cursors are positioned at **52.0/0.0042v** and **107.0/-0.0024v**, and the crack depth is 121mm or 4.7 inches.

This completes Section VI of this tutorial, covering determination of the depth of surface-opening cracks. Repeat the action steps in this section until you are thoroughly familiar with the methods described. The next section will describe the testing of concrete plates in contact with soil.

Section VII: Plates in Contact With Soils

Introduction

A common problem in the evaluation of plate structures is detecting voids under or behind concrete slabs in contact with soils. The absence or loss of subgrade support for a horizontal slab can result in damage when it is subjected to heavy loads, such as equipment on warehouse floors, trucks on highway pavements, or airplanes landing on runways. The impact-echo method can be used to detect voids under concrete slabs in these and similar situations.

This application follows from concepts introduced in Chapter 3 of *Sansalone and Streett* (pp. 42-45), based on the reflection and refraction of P-waves at an interface between two solid layers with different acoustical properties. The case considered here is that of a concrete plate (upper layer) in contact with soil, where the depth of the soil is great enough that no wave reflections from within that layer reach the transducer. Only wave reflections from within the concrete or from the concrete/soil boundary are significant. The acoustic impedance of concrete is several times larger than that of typical soils. As a result, when a stress wave encounters a concrete/soil interface, some of the wave energy is transmitted and some is reflected. For more details, see Chapter 13 of *Sansalone and Streett* (pp. 135-142).

Voids Under Plates

Detecting voids under concrete plates is one of the simplest applications of the impact-echo method. It relies on the clear and easily recognizable difference between waveforms and spectra obtained from plates in contact with soil, on the one hand, and plates in contact with air (a void under the slab) on the other.

Figure VII-1 shows a typical set of results obtained from an impact-echo test on a concrete plate in contact with soil. The waveform shows periodic displacements caused by P-wave reflections within the concrete plate, but because energy is lost to the soil each time a P-wave is incident on the concrete/soil interface, the amplitude of the displacements (indicated by the signal voltage) decays rapidly. The corresponding spectrum shows a single peak corresponding to the frequency of P-wave reflections from the concrete/soil interface. Note however, that the peak is somewhat rounded and is broader than those obtained from plates in contact with air (for example, see record 1 in the open file, or Figure III-1 in this manual). In Figure VII-1 only a few wave reflections were recorded before the signal decayed to an undetectable level.

For comparison, Figure VII-2 shows a typical result obtained from an impact-echo test on the same plate at a location where a void exists in the soil just below the plate. In this case P-wave reflections occur from a concrete/air interface at the bottom of the plate. Because virtually all of the wave energy is reflected at a concrete/air interface, surface displacements caused by the arrival of reflected P-waves decay more slowly compared to those reflected from a concrete/soil interface. The response is essentially the same as that obtained from a simple concrete plate in contact with air. The spectrum exhibits a very sharp, high amplitude peak corresponding to the P-wave thickness frequency. If the concrete slab is relatively thin (about 150mm or less) a lower frequency, lower amplitude peak, labeled $\mathbf{f_{flex}}$ in Figure VII-2(c), may also be present, as a result of flexural vibrations of the unsupported portion of the plate above the void. Flexural vibrations occur because the unsupported section above the void is restrained at its edges where it contacts the soil. The response is similar to that produced by an impact above a shallow delamination (see p. 55). However, because the thickness of the slab is relatively large, the amplitude of the flexural vibrations is smaller relative to the P-wave thickness response.

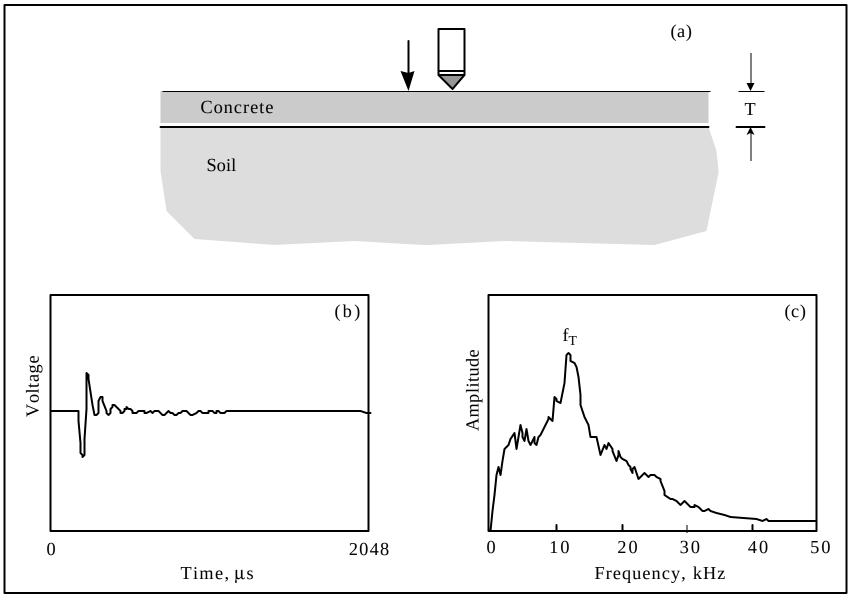


Figure VII-1. The impact-echo response of a concrete slab on soil subgrade: (a) cross-section, (b) waveform, and (c) spectrum.

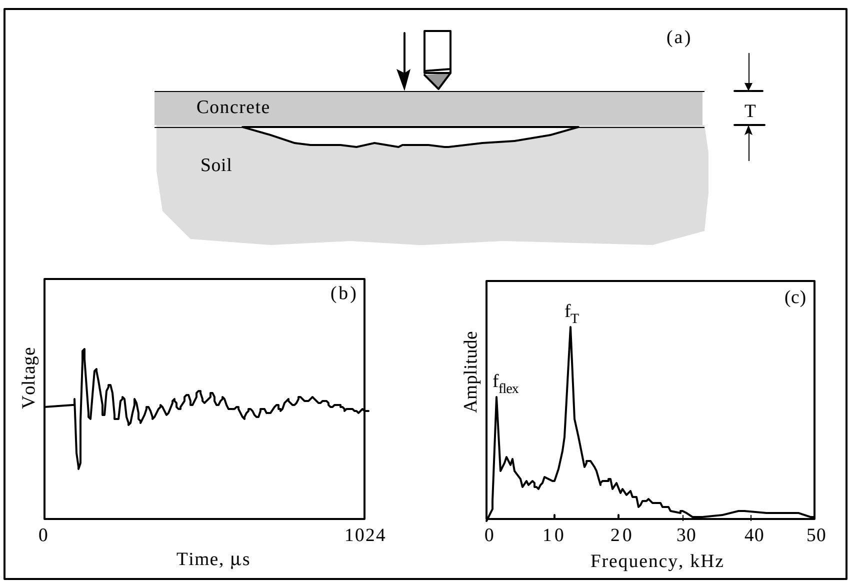


Figure VII-2. The impact-echo response obtained from a concrete slab at a location where a void exists in the soil subgrade: (a) cross-section; (b) waveform; and (c) spectrum**.**

Identifying Voids Under a Concrete Slab

1. Start the **ImpactDemo** program and open the existing file **c:\ImpactDemo\TestFile**. Records 19 – 24 in this file are from tests carried out to locate voids in the soil beneath a concrete warehouse floor with a nominal thickness of 152mm (6 inches).

2. To open record 19 click the **Number** box in the lower left of the screen [Keyboard: press "**Alt+B**"], enter "**19"**, and press the **Enter** key. Note the similarity between this record and the results shown in Figure VII-2. It is a test over a void in the soil beneath the floor. The P-wave reflections associated with the 14.2 kHz thickness frequency decay slowly, indicating that the bottom of the slab is a concrete-air interface. The low frequency component in the waveform, which appears as the 1.5 kHz peak in the spectrum, is the result of flexural vibration in the slab above the void. To remove the low-frequency component, place the spectrum cursor at about 10 kHz and click **Filter Low Freq**. The resulting waveform is similar to a decaying sine wave with a frequency of 14.2 kHz.

3. Open record 20. The spectrum peak at 14.6 kHz indicates that the slab is 134mm (5.3 inches) thick at this point. The rapid decay in the waveform indicates that stress wave energy was transmitted through a concrete/soil interface and lost to the soil beneath the slab. When this happens, the waveform contains little useful information in the region beyond where it decays to a small fraction of its original amplitude. A simple test can verify this. Click on the waveform with the mouse to place the active cursor at about 1000 μs, and click the **Cut Waveform** button. This removes (sets equal to zero) that portion of the waveform to the right of the cursor, and calculates the spectrum using only that portion to the left. Click the button several times, and note the very small change in the spectrum when the right half of the waveform is deleted or added.

4. When there is a void beneath a slab, the low frequency flexural vibration can be strong, as it is in record 19, or it can be weak or absent, depending on the thickness of the slab and the size of the void. The key to identifying the presence of a void beneath a slab on soil is the rate of decay of the signal that results from P-wave reflections. Record 21 is an example of a test over a void in which the flexural vibration is relatively weak, and record 22 is an example of test in which it is almost nonexistent. To verify that records 19 and 22 are similar in terms of the decay of reflected P-waves, open record 19, place the waveform cursor at about 10 kHz, and click the **Filter Low Freq** button at the lower right of the screen. This removes the low frequency components and the resulting waveform, which is similar to a slowly decaying sine wave, and looks very much like the waveform for record 22.

5. Records 23 and 24 are from tests where the slab is in contact with soil. This is indicated by the rapid decay in the P-wave reflections in the waveform, and by the relatively broad main peaks in the spectra. To compare the peak in the spectrum of record 23 with that in record 22, for example, open record 23, click the text box next to the **Compare** button, enter "**22"**, and press the **Enter** key. This causes the spectrum from record 22 to be overlaid as a green dashed line on the spectrum of record 23. Note that the main peak in record 23 (concrete on soil) is broader than that for record 22 (void beneath the concrete). The sharp narrow peak in record 22 is characteristic of P-wave reflections from a concrete/air interface at the bottom of the slab.

This completes Section VII of this tutorial, covering the detection of voids beneath plates in contact with soils. Repeat the action steps in this section until you are thoroughly familiar with the methods described. The next section will describe the testing of plates consisting of two layers, such as concrete patches and concrete with asphalt overlays.

Section VIII: Plates Consisting of Two Layers

Introduction

The impact-echo response of structures consisting of two layers is described in detail in Chapters 14, 15 and 16 of *Sansalone and Streett* (pp.143-166). In this section of the tutorial two cases are examined: (1) a concrete overlay on a concrete slab, and (2) an asphalt overlay on a concrete slab. Concrete on concrete is a special case of a simple plate, because the two layers have the same acoustic impedance. Asphalt on concrete presents a different and more complicated case, because the acoustic properties of asphalt (including wave speed and acoustic impedance) differ from those of concrete.

Debonding at the Interface of a Concrete Overlay on a Concrete Slab

In the case of a concrete overlay on a concrete slab, wave reflections from the concrete/concrete interface occur only if the two layers are debonded or weakly bonded. The principal use of impact-echo is in identifying areas where the overlay (the top layer of a slab poured in two layers, or a concrete patch, for example) is debonded or only weakly bonded to the parent concrete. The test records used here are from tests on a concrete floor that was poured in two layers, with effective bonding in some areas and little or no bonding in others. The floor had a nominal thickness of 154mm (about 6 inches) and had been poured in two layers of approximately equal thickness. An impact-echo test on a solid slab of known thickness was used to determine the P-wave speed of 3780 m/s. Using the equation **f =** β**Cp/(2d)** the frequency of P-wave reflections from the full thickness (areas where the two layers are strongly bonded) was found to be 12.2 kHz, while the frequency of reflections from an unbonded interface at a depth of about 77mm was found to be 24.5 kHz.

1. Start the **ImpactDemo** program and open the file **c:\ImpactDemo\TestFile.dat**, provided as part of the software for this tutorial. Records 25 – 30 in this file are from tests on the 2-layered floor described above. Open record 25 (click the **Number** text box at the lower left of the screen [Keyboard: press "**Alt+B**"], enter "**25**" and press the **Enter** key). The dominant frequency peak is at 12.2 kHz, indicating that the response is from a point where the two layers are bonded and the composite thickness is 155mm, or about 6.1 inches.

   Recognizing Transducer Resonance. The low frequency peak at 1.0 kHz is an artifact, resulting from excitation of the natural resonance of the piezoelectric transducer element and the brass block to which it is attached. This "transducer resonance" at 1.0 kHz is often excited when an impact is made close to the transducer, and it is especially strong when the concrete surface being tested is very smooth. It is responsible for the low-amplitude, very low frequency component in the waveform. To remove this component by digital filtering, place the waveform cursor at a frequency slightly above the 1.0 kHz peak (2 – 3 kHz, for example) and click **Filter Low Freq** [Keyboard: press "**Alt+Q**"]. Click this button several times to add and remove the low frequencies, and note the change in the waveform and spectrum.

   Removing the R-wave. In this waveform the amplitude of the R-wave is large compared to the remainder of the waveform. In cases such as this it is sometimes desirable to remove the R-wave from the waveform, to reduce its contribution to high frequencies in the spectrum. To observe this effect, place the active waveform cursor at the point where the R-wave overshoot returns to zero voltage (at about 246 μs after the trigger point, indicated by the label on the cursor), and press **Cut R-wave** [Keyboard: press "**Alt+R**"]. Click this button several

times, and observe the change in the waveform and spectrum. The level of high frequency "noise" in the spectrum is reduced when the R-wave is removed. In this case the effect is relatively small; however, when the amplitude of the R-wave is very much larger than the remainder of the waveform, its removal has a more dramatic effect.

Clipping the R-wave. Restore the R-wave, click the **1 Clip Level** text box [Keyboard: press "**Alt+1**"], enter 0.2 and press **Enter**. Portions of the R-wave outside the range ± 0.2 volts are "clipped" or removed from the waveform, and the vertical scale in the waveform is expanded to 0.2 volts. The effect on the spectrum is almost the same as removing the R-wave.

After the transducer resonance has been filtered out and the R-wave clipped, the screen should appear as in Figure VIII-1. There is a strong, sharp peak in the spectrum at 12.2 kHz with very little additional structure. This is reflected in the waveform, which is clearly dominated by a single frequency.

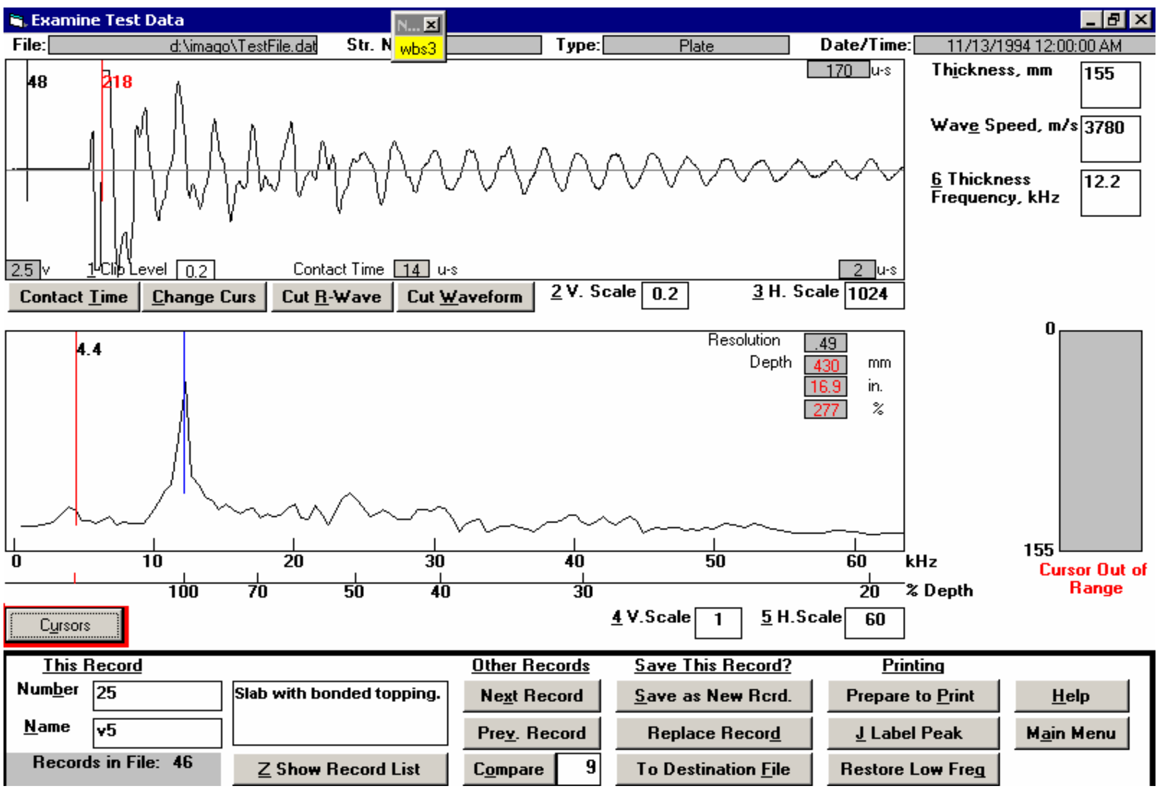


Figure VIII-1. Record 25 with the transducer resonance filtered out and the R-wave clipped at 0.2 volts.

2. Click **Next Record** [Keyboard: press "**Alt+X**"] to open record 26. The main peak in this case lies at 23.4 kHz, corresponding to P-wave reflections from a depth of 81mm, or about 3.2 inches (these numbers appear in the gray boxes at the upper right of the spectrum graph, and in the plate cross-section at the right of this graph).

   Analysis and Interpretation: Wave reflections from a depth of 81mm indicate that the two layers of concrete are debonded. Note that in addition to the transducer resonance peak at 1.0 kHz, there is a small peak at about 2 kHz, probably due to flexural vibrations in the thin top

layer of concrete. To see the effects of removing these low frequency components, place the spectrum cursor at about 10 kHz, and click **Filter Low Freq.** The effect of "cutting" or removing the R-wave can be seen by placing the active waveform cursor at about 228 µs and clicking the **Cut R-Wave** button. The result should appear as in Figure VIII-2, showing a single dominant frequency at 22.9 kHz, corresponding to a depth of 82mm or 3.2 inches.

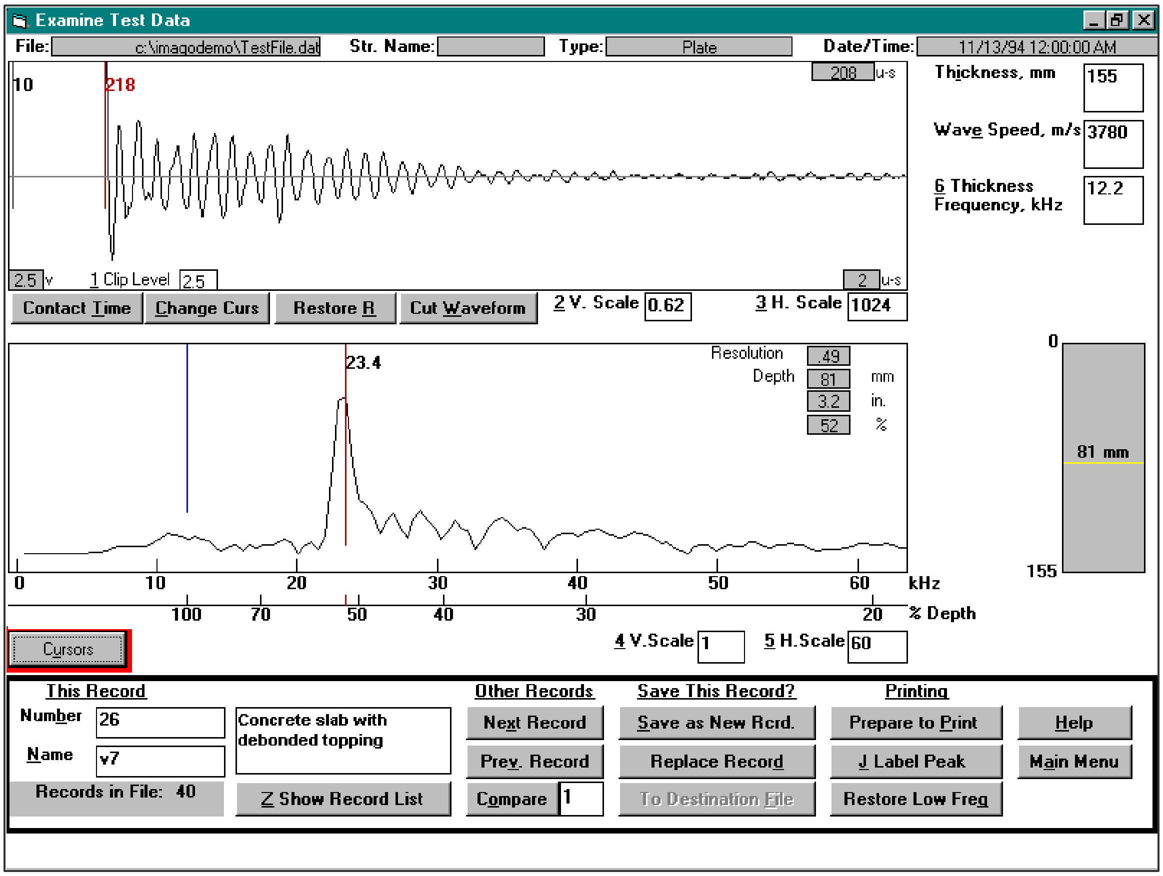


Figure VIII-2. Record 26 with the low frequency components filtered out and the R-wave removed.

3. There next four records, 27 through 30, are tests on the same 2-layered slab. Record 28 is from a test where the layers are bonded (it shows the effects of a relatively large transducer resonance) while records 27, 29 and 30 show debonding at the interface.

Concrete With Asphalt Overlay

When concrete slabs, such as bridge decks, have asphalt overlays, the problem is one of a two-layered structure in which the upper layer—the asphalt layer—is acoustically softer than the lower layer of concrete. The P-wave speed is lower in asphalt than in concrete (typically 2500 – 3000 m/s in asphalt and 3800 – 4500 in concrete). The coefficient of reflection at an asphalt/concrete interface is about 0.20. This means that if the two layers are strongly bonded, P-wave reflections due to the acoustic mismatch will be too weak to be detected (see p. 44 in *Sansalone and Streett*), and the P-wave reflections will occur from the bottom of the concrete layer. The layered structure will respond as a single plate, with the added complication of different

wave speeds in the to layers. In this case the response due to P-wave reflections from the bottom of the concrete is called the “composite thickness response”. Experience has shown, however, that even when the two layers are well bonded there is sometimes a significant fraction of unbonded area due to the coarseness of the asphalt, and this is sometimes sufficient to cause P-wave reflection (see Chapter 15 of *Sansalone and Street*, pp. 151-158). The P-waves are reflected from a large number of small air inclusions at the interface, rather than from the area of contact between asphalt and concrete. Thus the basic response of a concrete slab with a bonded asphalt overlay can consist of two components: (1) a relatively weak response caused by multiple P-wave reflections between the impact surface (the top of the asphalt overlay) and the asphalt/concrete interface; and (2) a dominant composite thickness response caused by multiple P-wave reflections between the impact surface and the concrete/air interface at the bottom surface of the concrete. If the fraction of unbonded area at the interface is low, the peak associated with the first response will be weak, or absent altogether. If there is debonding at the interface, there will be complete P-wave reflection from that level, and no response from the concrete layer below. A complete analysis of P-wave propagation in such a structure can be found in Chapter 16 of *Sansalone and Streett* (pp. 159-161). Because the two layers have different acoustic properties, the structure cannot be treated as a simple plate. It is treated as a special class in impact-echo testing as explained in the following paragraphs.

4. Return to the **Main Menu** screen, click **Open Test Data File**, and create and open a new file **c:\ImpactDemo\Overlay**. After returning to the **Main Menu** screen, click **Describe Structure** and from the **Choose Structure Type** option box that appears, select **Plate With Overlay** and click **OK**. The **Plate With Overlay** screen appears, as shown in Figure VIII-3.

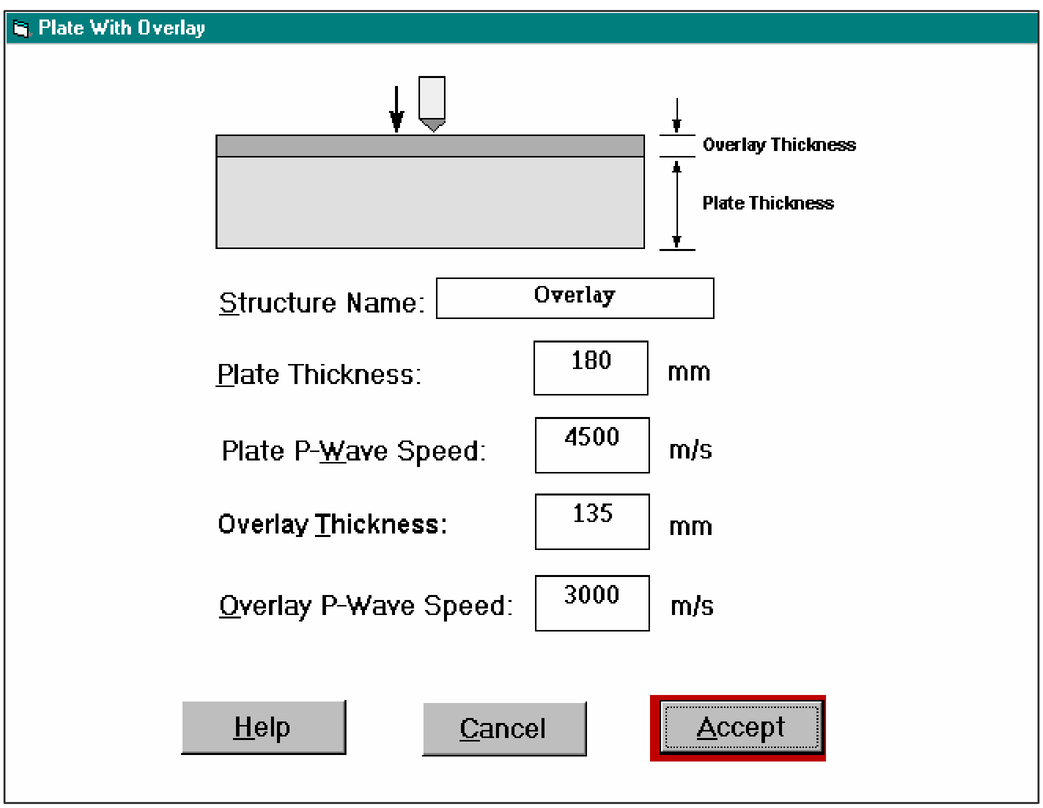


Figure VIII-3. The **Plate With Overlay** screen

Enter "**Overlay**" as the structure name, 180mm as the plate (concrete) thickness, 4500 m/s as the plate P-wave speed, 135mm as the overlay thickness, and 3000 m/s as the overlay P-wave speed. When these values have been entered click **Accept**. Click **Accept** again on **the Parameters for Data Acquisition** screen.

5. At the **Main Menu** screen, click **Begin Impact-Echo Test** to enter the **Begin Testing** screen for the **Plate With Overlay** structure type (Figure VIII-4).

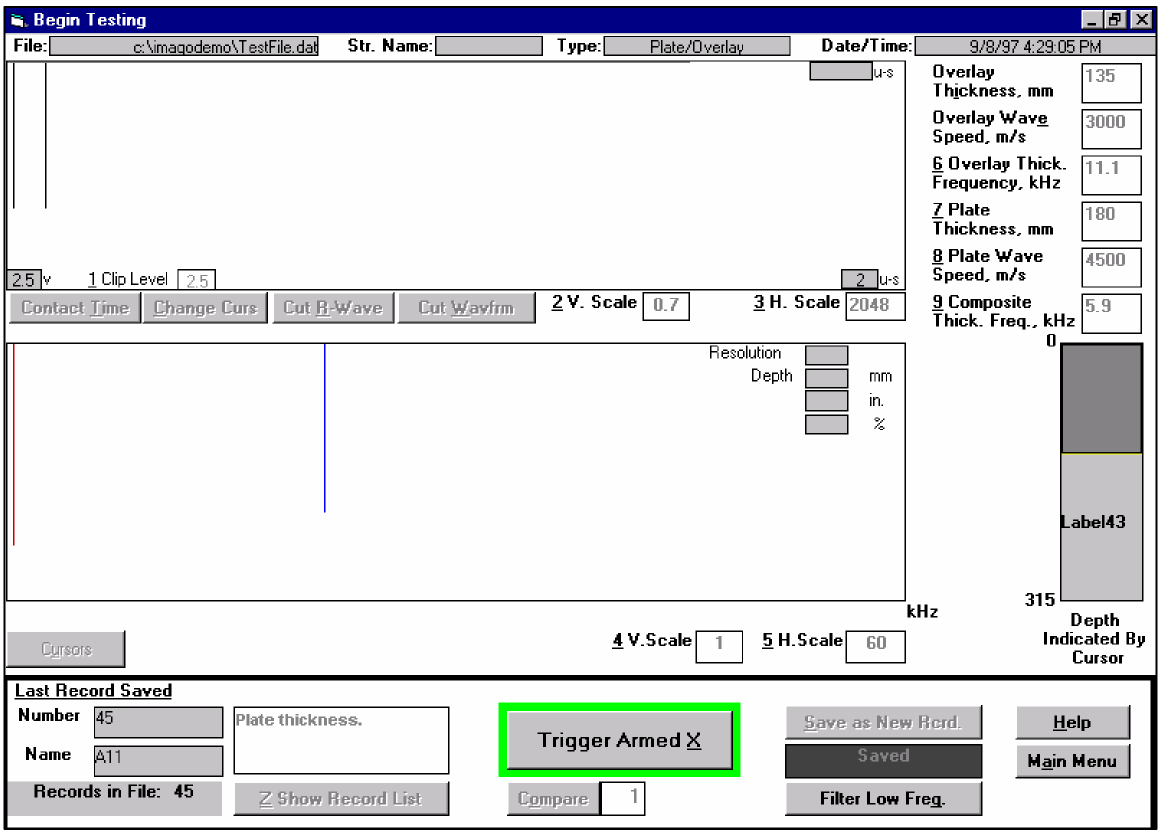


Figure VIII-4. The **Begin Testing** screen for the **Plate/Overlay** case.

Note that this screen differs from the screen for simple plates, in that there are six key parameters in the upper right of the screen: thickness and wave speed for both the concrete plate and the asphalt overlay, an overlay thickness frequency and a composite thickness frequency. The system is now ready to receive the results of a test on a concrete/asphalt structure with the estimated thickness and wave speed values shown in these boxes.

6. To view the results of tests on this concrete/asphalt structure, return to the **Main Menu** screen, and open the file **c:\ImpactDemo\TestFile.dat**. Records 31 – 35 in this file are from tests on a 180mm thick concrete bridge deck with an asphalt overlay having a nominal

thickness of 135mm. Wave speeds in the concrete and asphalt were found to be 4500 and 3000 m/s, respectively. Open record 31 (Figure VIII-5).

Analysis and Interpretation. On this screen the spectrum has two "thickness" lines: a blue line at 5.9 kHz that marks the composite thickness frequency (associated with reflections from the bottom of the concrete at a depth of 315mm beneath the asphalt surface), and a green line at 11.2 kHz that marks the expected frequency of reflections from the asphalt/concrete interface at a nominal depth of 135mm. Note also that the cross-section box at the lower right of the screen contains two layers, with the darker layer at the top representing the asphalt and the layer below the concrete. In this record, the main peak in the spectrum lies at 6.3 kHz, corresponding to a depth of 286mm, or 29mm above the nominal depth of the bottom of the concrete layer. This could be the result of a crack or delamination at that depth, but it could also mean that the asphalt and/or concrete have less than the nominal thickness at this point. Because there are two wave speeds and two thicknesses that are variables in this case, finding the correct combination of wave speed, thickness and frequency is not as straightforward as in the case of a simple plate.

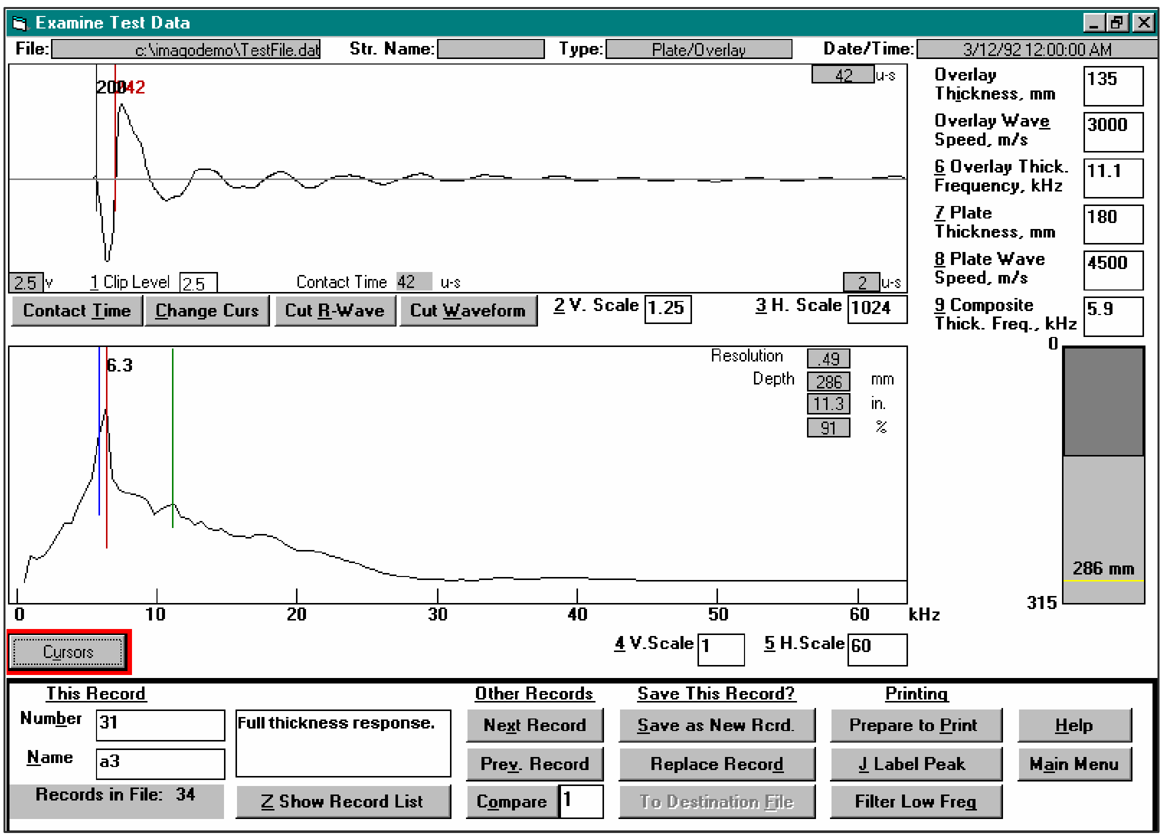


Figure VIII-5. A full thickness response for a 180mm thick concrete slab with a 135mm asphalt overlay.

7. The proximity of the main peak in the spectrum (6.3 kHz) to the expected full thickness frequency of 5.9kHz, makes it reasonable to assume that one or more of our estimates of thickness and wave speed are incorrect. To adjust one or more parameters click the text box labeled **9 Composite Thick. Freq.** [Keyboard: press "**Alt+9**"]. Enter the observed

composite thickness frequency of 6.3, and press **Enter**. The **Layered Plate Parameter Calculations** screen appears (Figure VIII-6).

Analysis and Interpretation. The option box on the left presents the user with two choices. **Option1** is for a case where there is a full thickness frequency peak, as well as a weaker due to P-wave reflections from the interface. Because there is only one distinct peak in record 31, **Option2** is selected. This option presents the user with several choices of variables to change and adjust. If the single peak present is assumed to be the composite thickness frequency peak, then the wave speeds and thickness of each layer are adjustable parameters. If two or more of these are not known with certainty, it is difficult to proceed. We assume in this case that the wave speeds have been separately measured and are known to be accurate. This means that the discrepancy between the expected and observed composite thickness frequencies (5.9 and 6.3 kHz) is due to incorrect values of thickness for one or both of the layers. In this case we assume that it is the asphalt thickness that is not accurately known. Having entered 6.3 as the full thickness frequency, select "**Overlay Thickness**" as the variable to be calculated, and click **Calculate** (make certain that **Option2** on the left has been selected). The overlay thickness is recalculated as 118mm. Click **Accept** to return to the Examine Test Data screen, and note that the full thickness frequency marker is now at the main peak (6.3 kHz). The frequency associated with reflections from the interface has been automatically recalculated as 12.7 kHz, and the green marker line on the spectrum has been moved accordingly. If the thickness of each layer is known and the wave speed in one layer is uncertain, this method can be used to calculate the true wave speed. The point to remember is that in order to proceed with certainty, three of the four adjustable variables (thickness and wave speeds) must be known to obtain a reliable estimate for the fourth variable.

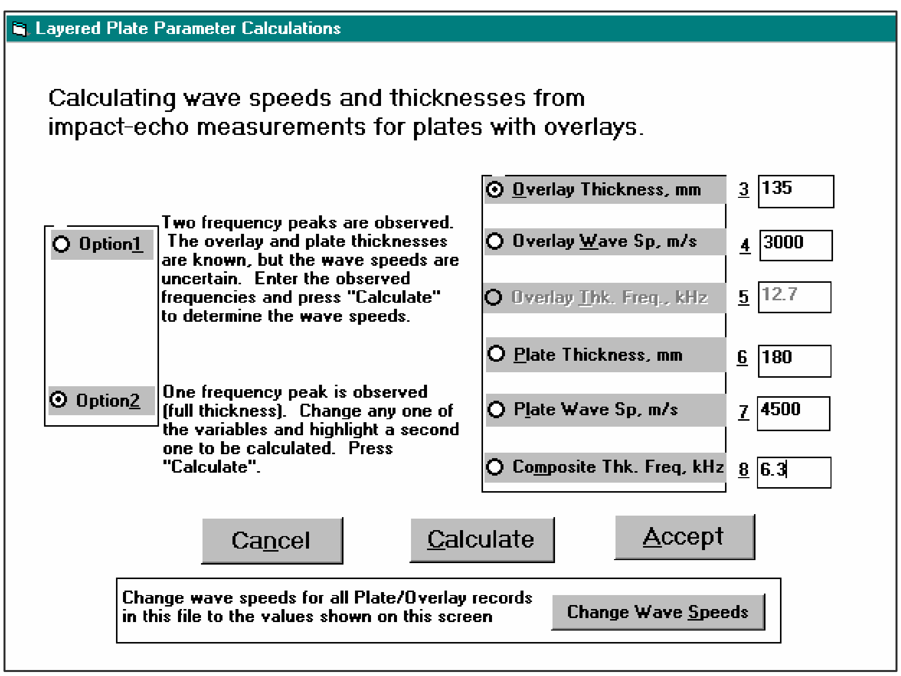


Figure VIII-6. The **Layered Plate Parameter Calculations** screen.

8. Use the mouse to place the spectrum cursor at frequencies between the two thickness lines at 6.3 and 12.7 kHz, and to the right of the 12.7 kHz line, and observe the level of the horizontal cursor in the cross-section box at the right. It should be clear from this exercise that frequencies between the green and blue lines represent P-wave reflections from within the concrete layer, while frequencies to the right of the green line represent P-wave reflections from within the asphalt layer. In searching for cracks or delaminations within the concrete, look for peaks between 5.9 and 11.2 kHz.

9. Open record 32. The dominant peak in the spectrum is at 11.2 kHz, the frequency associated with P-wave reflections from the asphalt/concrete interface. This indicates debonding at the interface. In this case no information can be obtained about the concrete layer, because the P-waves are not transmitted across the debonded interface.

10. Open record 33. The dominant peak at 9.8 kHz indicates P-wave reflections from a depth of 162mm, or about 27mm below the asphalt/concrete interface, the approximate depth of the upper layer of reinforcing steel in the concrete. Delamination in the concrete at that level was confirmed by coring.

    Removing or dipping the R-Wave. In the waveform of Figure 33, the magnitude of the R-wave is very large compared to the remainder of the signal. To gain a clear picture of the frequencies contributed to the spectrum by the R-wave, place the active waveform cursor to the right of the R-wave (at 302 µs) and click **Cut Waveform**. The result is a spectrum showing that the large R-wave in this signal contributes a broad dome of frequencies to the spectrum with a maximum at about 9 kHz. Next click **Restore W** and then **Cut R-Wave**. Cutting, or removing, the R-wave eliminates the broad dome of frequencies it contributes to the spectrum, leaving a sharp, narrow peak due to P-wave reflections from the delamination. A similar effect can be obtained by clipping the R-wave. With the R-wave restored, click the **1 Clip Level** text box [Keyboard: press "**Alt+1**"], enter 0.06 as the clip level, and press the **Enter** key. The advantage of using the clip level rather than removing the R-wave is that during testing the clip level can be set at an appropriate level and the R-wave will be automatically clipped as each test is performed. The full R-wave can be recovered by raising the clip level to a value a higher value.

11. Open record 34. The dominant peak at 7.3 kHz is the result of P-wave reflections from a depth of 239mm beneath the asphalt surface. This was found to be the result of delamination at a lower layer of reinforcing steel.

12. Open Record 35. The dominant peak at 15.6 kHz corresponds to a depth of 96mm, within the asphalt layer. On further inspection this was found to be the result of a debonded asphalt patch.

This completes Section VIII of this tutorial, covering impact-echo testing of plates with two layers. Repeat the action steps in this section until you are thoroughly familiar with the methods described. The next section will describe testing to locate voids in the grouting of tendon ducts in post-tensioned structures.

Section IX. Voids in the Tendon Ducts of Post-Tensioned Structures

Introduction

Serious problems can develop in post-tensioned structures if voids are present within the grout that is used to fill the tendon ducts . Voids in the grout can occur along the tendon trajectory due to blockages, improper grouting procedures, grout material problems, and construction oversight. Inadequate grouting may allow water to penetrate into the ducts, causing corrosion of the steel tendons leading to failure of the structure.

The impact-echo method can be used to detect voids in grouted tendon ducts in many, but not all, situations. The method's applicability depends on the geometry of a structure and the locations and arrangement of tendon ducts. Just as is the case for other types of flaws, small voids in tendon ducts cannot be detected if the ratio of the size of the void to its depth beneath the surface is less than about 0.25 (see *Sansalone and Streett*, pp. 84-85). In addition, complicated arrangements of multiple ducts, such as often occur in the flanges of concrete I-beams, can preclude detection of voids in some or all of the ducts. In other cases, portions of structures can be successfully tested and information can be gained that permits an engineer to draw conclusions about the condition of the grouting along the length of the duct. The simplest case, and the one described here, is that of post-tensioned ducts in a plate structure, such as a bridge deck or the web of a large girder, in which there is only one duct directly beneath the surface at any point. **In all cases, the impact-echo method is restricted to situations where the walls of the ducts are metal rather than plastic**.

Effective use of the impact-echo method for detecting voids in grouted tendon ducts requires knowledge of the location of the ducts within the structure. This information is typically obtained from plans and/or the use of magnetic or eddy-current cover meters to locate the centerlines of the metal ducts. Once the duct locations are known, impact-echo tests can be performed to search for voids.

Metal Ducts

Tendon ducts in post-tensioned structures are typically made of steel with a wall thickness of about 1mm (0.04 inches). The space not occupied by tendons inside the duct is (or should be) filled with grout, which has an acoustic impedance similar to that of concrete. Because the wall thickness of a duct is small relative to the wavelengths of the stress waves used in impact-echo testing, and because a steel duct is a thin layer of higher acoustic impedance between two materials of lower acoustic impedance (concrete and grout), it is transparent to propagating stress waves. Therefore, the walls of thin metal ducts are not detected by impact-echo tests. (In contrast, plastic ducts have a lower acoustic impedance than concrete or grout, and they are not transparent, complicating attempts to detect voids within plastic ducts.)

The Response of Grouted and Ungrouted Tendon Ducts

The frequency of multiple P-wave reflections from a grout/steel interface is given by $\mathbf{f} = \mathbf{C_p}/4\mathbf{d}$, where $\mathbf{C_p}$ is the P-wave speed and **d** is the depth from which the P-waves are reflected. The response from a group of strands in a fully grouted duct can be predicted based on the distance, **d**, to the nearest strands. The frequency response obtained from steel post-tensioning strands is usually slightly higher than predicted by this equation. By comparison, the frequency of P-wave reflections from a concrete air interface are given by $\mathbf{f} = 0.96\mathbf{C_p}/2\mathbf{d}$. The frequency of P-wave reflections from a void will be approximately twice that of P-wave reflections from steel tendons.

(The differences between P-wave reflections from a concrete/steel interface and those from a concrete/air interface are explained in more detail in Chapter 17 of *Sansalone and Streett*, pp. 167-171.)

Besides being reflected from the steel strands in a grouted duct, P-waves are also refracted through the duct and reflected from the opposite surface of the plate. Because the wave speeds in concrete and grout are similar, and because the cross-sectional area of the steel strands is relatively small, the full-thickness response of a structure containing a fully grouted duct is very close to that for the solid structure without a duct.

The schematic illustrations in Figure IX-1 summarize the three basic responses for a plate containing a single post-tensioning duct in any particular cross-section: (a) the response of the solid plate; (b) the response over a fully grouted duct; and (c) the response over a duct containing a void. In (b) the full thickness frequency peak, $\mathbf{f_T}$, is at or only very slightly below the frequency of the response from a solid plate, (a), and the response due to wave reflections from the steel tendons is given by the equation $\mathbf{f_{steel}=C_p/4d}$. In (c) the thickness frequency, $\mathbf{f_T}$, is shifted downward due to the additional path length traversed by P-waves diffracted around the void, and by the reduced stiffness of the plate in the vicinity of the void. The frequency of P-wave reflections from the void is given by $\mathbf{f_{void}=0.96C_p/2d}$, which means that $\mathbf{f_{void}}$ exceeds $\mathbf{f_{steel}}$ by a factor of about two, even though the void and the steel are about the same distance beneath the surface.

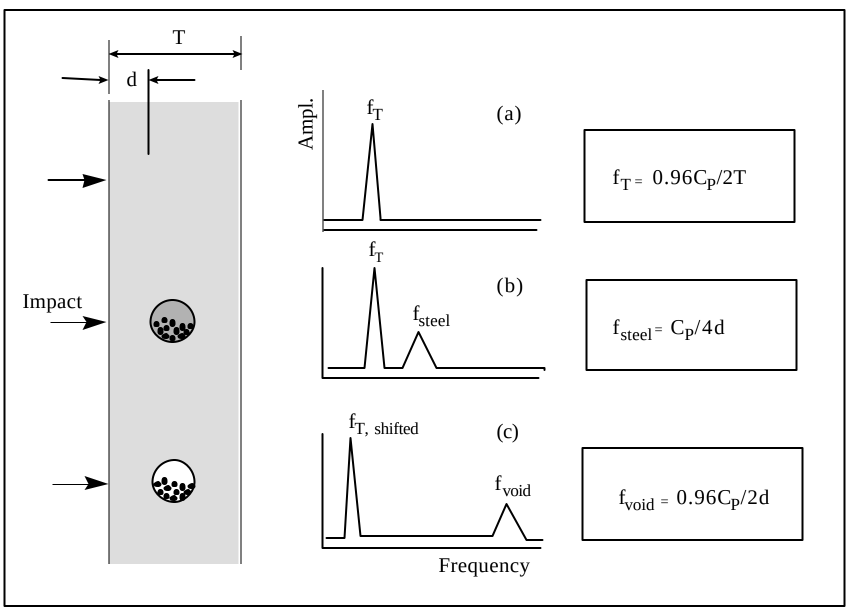


Figure IX-1. Schematic diagram showing the three types of response for a plate containing post-tensioning ducts: (a) solid plate; (b) grouted duct; and (c) duct containing a void.

These responses are illustrated using several records from impact-echo tests on a post-tensioned girder in a concrete bridge. The web of the girder behaved as a simple plate (lateral dimensions greater than five times the thickness). It had a thickness of 0.25m, or about 10 inches. Positions of the ducts were determined using a magnetic cover meter. The approximate depth of the duct

beneath the surface was about 80mm, or a little over 3 inches. The wave speed was measured from impact-echo tests on a region of known thickness, and found to be 3900 m/s. Using the equations given above, the thickness frequency of the solid plate was calculated to be 7.8 kHz, the frequency associated with P-wave reflections from a fully grouted duct was estimated to be 12.2 kHz, and the frequency for a void was estimated to be 24.4 kHz. The latter two estimates are approximate, because the depth of a void or of the tendons varies according to their location within the duct.

1. Open the file **c:\ImpactDemo\TestFile.dat** (see p. 26) and open record 37. This record, from a test on a solid portion of the web, is typical of the response of a solid plate, and exhibits a thickness frequency peak at the expected value of 7.8 kHz.

2. Open record 38. This record is from a test over a fully grouted tendon duct (Figure IX-2). The peak at 13.7kHz is due to P-wave reflections from the grout/steel tendon interface. Its frequency is slightly higher than the estimated value of 12.2 kHz, which is common for P-wave reflections from multiple steel tendons.

3. Open record 39. This record is from a test over a duct that is ungrouted. The peak associated with the thickness frequency is reduced to 3.9 kHz, well below the solid thickness frequency of 7.8 kHz, and there is a peak at 24.4 kHz, the expected frequency of the response from a void at a depth of about 80mm.

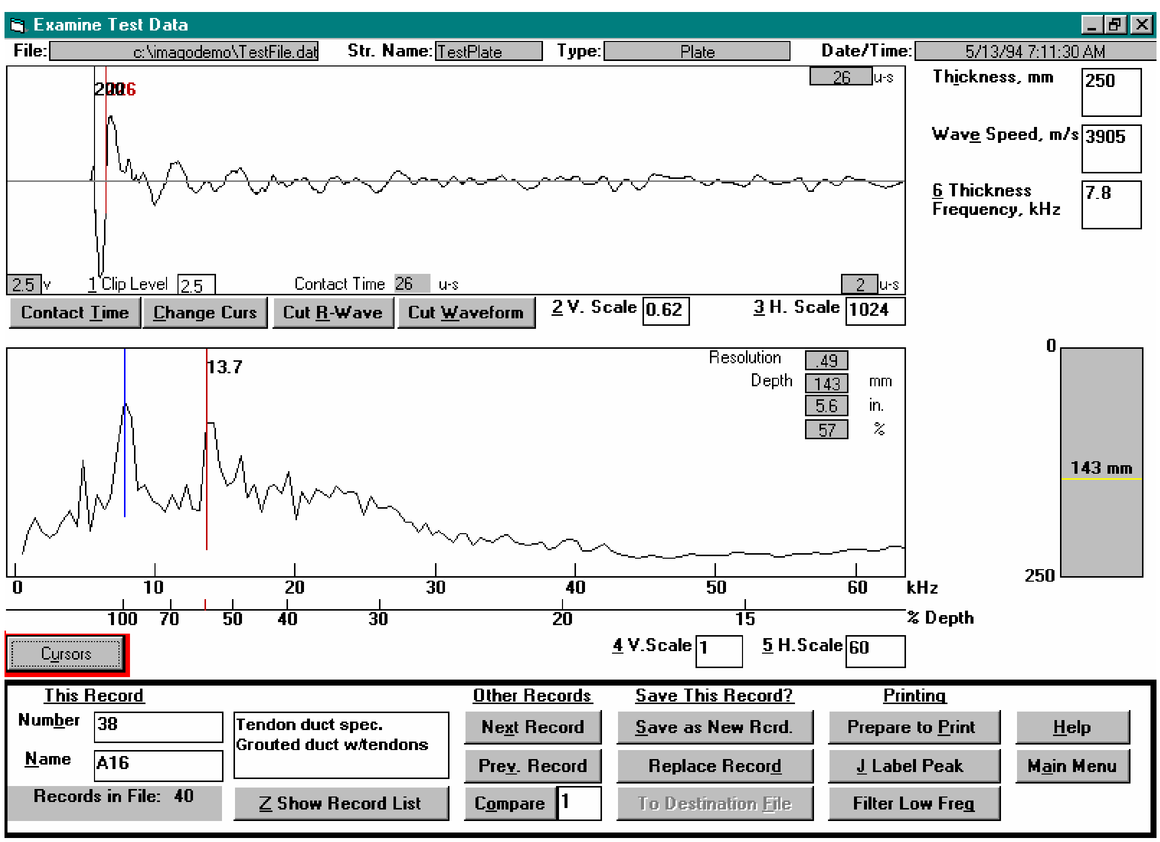


Figure IX-2. The results of a test over a fully grouted tendon duct (record 38).

This completes Section IX, covering testing to locate voids in the grouting of tendon ducts in post-tensioned structures.

Detailed explanations and illustrations of the impact-echo response of structures other than concrete plates, such as hollow cylinders (pipes and tunnel and mine shaft liners), circular, square and rectangular beams and columns, and masonry structures, can be found in *Sansalone and Streett.*

The final section of the manual covers practical aspects of field testing and interpretation of impact-echo test results.

Section X: Tips on Signal Interpretation

Introduction

To use the impact-echo method effectively, one must learn to interpret and classify graphical patterns in the waveforms and spectra. This section provides advice and insights on this topic.

Evaluating the waveform.

The waveform is the raw response of an impact-echo test. It contains all of the information provided by the test, but in a form that often makes it difficult to extract key features of the response, such as the transient resonant frequencies associated with multiple P-wave reflections. Nevertheless, it is the features of the waveform that allow one to determine when a recorded test is valid. A common mistake by new users of impact-echo is to ignore the waveform altogether, and to base an interpretation solely on the spectrum. The waveform always contains useful information, and it should be examined as part of the interpretation of each test.

Valid and Invalid Waveforms. It is very important to recognize when recorded data are invalid—that is, when something has gone wrong with the test, and the data should be discarded. A valid waveform, indicating a successful test, will consist of horizontal or zero-voltage segment at the beginning, followed by a distinct R-wave (except in the case of surface-opening cracks) and a periodic displacement pattern caused by multiple reflections of stress waves. Many examples of valid waveforms can be found in figures in this manual and in the accompanying test records in the file **c:\ImpactDemo\TestFile.dat**. That portion of the waveform following the R-wave contains the important information on resonant frequencies. **Impact-E** software has the capability to automatically screen or check incoming waveforms to determine whether they have the characteristics of a valid impact-echo test. (See "Program Parameters" Option in Section I, or see "Screening for Bad Signals" in the on-board Help System for **Impact-E** Software.) If an incoming signal does not have the characteristics of a valid impact-echo test, the computer will emit a loud "buzzer" signal, and the waveform will be plotted as a red line.

Invalid waveforms can result from rough surfaces on the concrete, dirt, or other foreign material on the surface, premature triggering, loss of contact between the transducer and the surface, accidental movement of the transducer during the test, or a host of other causes. Examples of bad waveforms resulting from some of these causes are shown in Figure X-1.

The waveform in Figure X-1(a) is the result of a stray electrical signal that triggered the data acquisition system prior to an impact. Stress waves generated by movement of the impact-echo hand-held unit generated the invalid waveform in (b). Stress waves caused by the vibration or impact of heavy equipment, jackhammers, etc. which are in contact with the structure being tested, can also cause the data-acquisition system to trigger in the absence of an impact if the stress waves generated are in the range over which a transducer is sensitive (typically about 500 Hz to 100 kHz). The waveform in (c) is an example of such a response. The spectra produced by invalid waveforms, especially the waveform in (c) are sometimes much like normal spectra, but are invalid because they are derived from an invalid source. Invalid waveforms are common, and should be rejected and the test repeated.

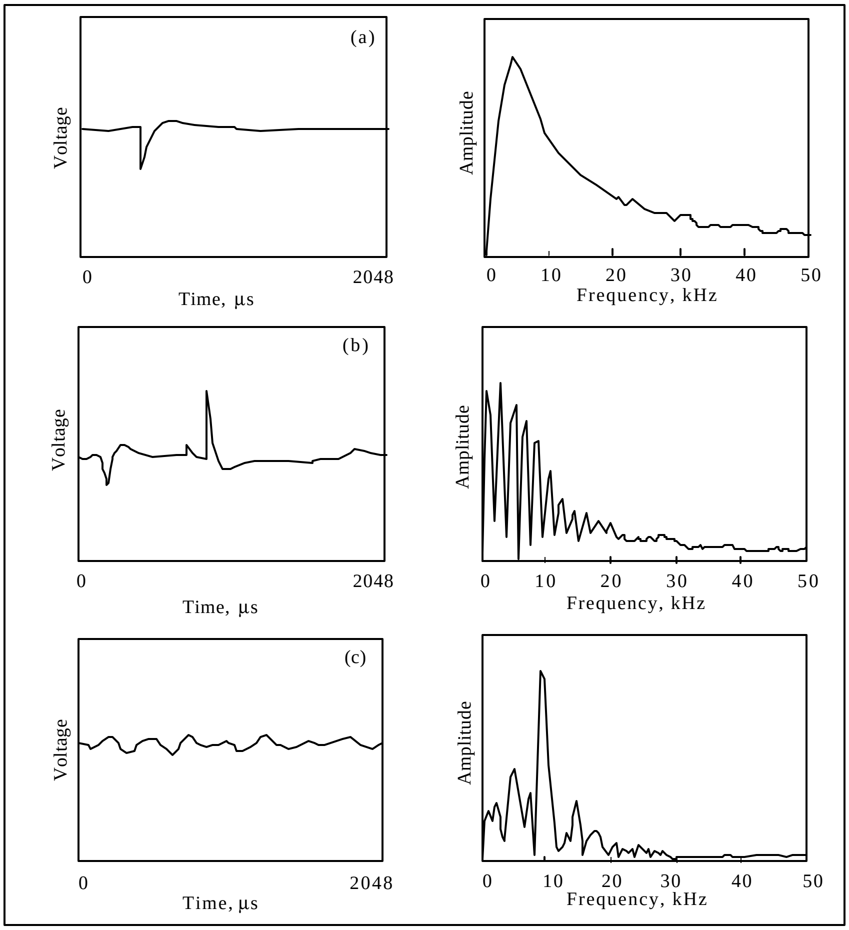


Figure X-1. Examples of "bad" waveforms (left) and their spectra (right).

Another example of an invalid waveform is shown in Figure X-2. This type of waveform is often observed when testing thin structures or mainly over very shallow delaminations. The response is generated by an impact of too large energy content (typically caused by using too large an impactor). Large surface displacements cause over-ranging of the transducer (the transducer produces a voltage greater than the maximum range of $\pm$ 2.5 volts) and intermittent loss of contact between the surface and the transducer. A normal waveform can often be obtained by reducing the force of the impact. Sometimes a "bad" waveform such as this provides evidence of the presence of very shallow delaminations.

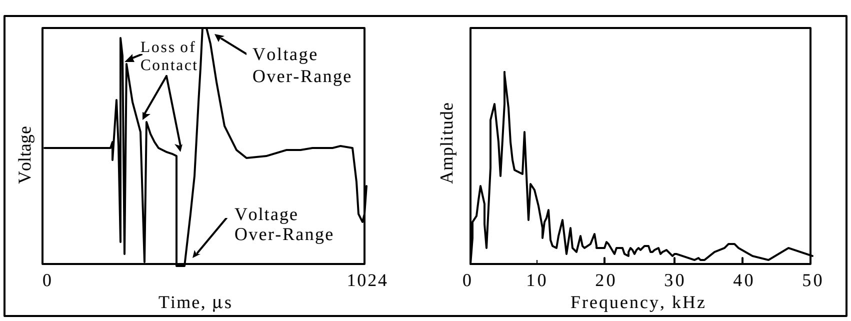


Figure X-2. Response produced over-ranging of the transducer and intermittent loss of contact with the surface.

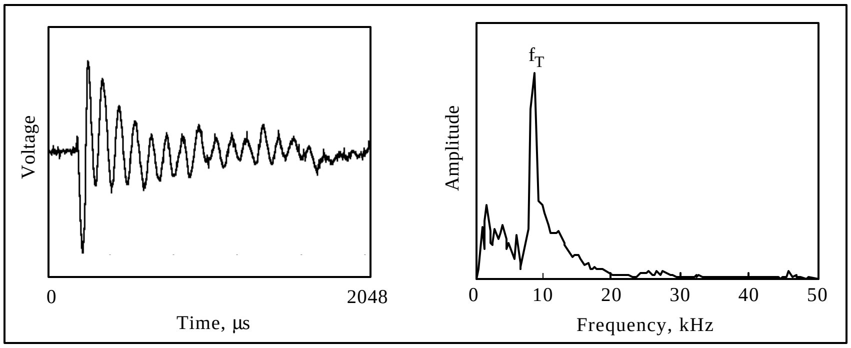


Figure X-3. A waveform mildly affected by electrical noise.

Sometimes impact-echo signals are affected, but not invalidated, by stray electrical noise. Figure X-3 shows a test in which the waveform contains a low-amplitude, high-frequency component, which produces a jagged appearance in an otherwise smooth curve. The effects of the noise are especially visible in the portion of the waveform prior to the arrival of the R-wave. In this case the amplitude of the electrical noise is too low relative to the R-wave and P-wave signals to produce a visible peak in the spectrum, and the test is valid.

Figure X-4 is an example of a test in which the electrical noise is more regular and has a larger amplitude. In this example which was obtained from a test on a solid, 250-mm thick plate, the thickness frequency, $\mathbf{f_T}$, is 7.8 kHz.

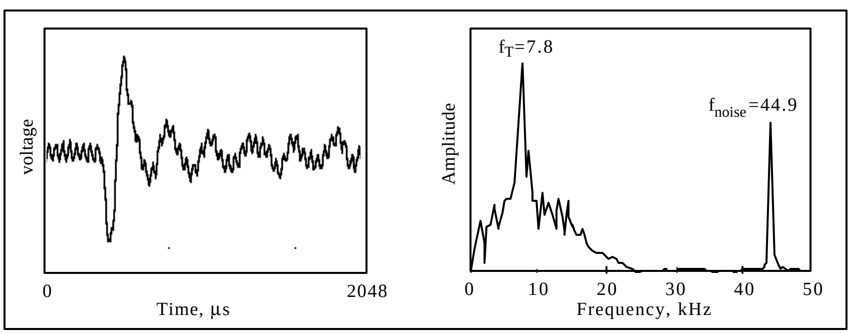


Figure X-4. A test result with electrical noise of relatively high amplitude.

The electrical noise appears in the spectrum as a sharp peak at 44.9 kHz. In this impact-echo test, the impact duration was approximately 46 micro-seconds, and the maximum frequency of useful energy in the impact-generated stress waves is about 27 kHz. This means that the 44.9 kHz signal could not have come from wave reflections within the structure. The uniform nature of the oscillations throughout the waveform (including prior to the arrival of the R-wave) and the distinct, sharp high-frequency response are characteristic of a stray electrical signal, which is easily recognized. In this case the validity and usefulness of the impact-echo test results are not affected by the electrical noise, even though it is a prominent part of the recorded signal.

The Importance of the R-wave.

Recognizing valid waveforms often centers on recognizing the features of the initial R-wave. **If a clearly defined R-wave does not appear at the beginning of the waveform, the signal will be identified as a "bad" signal, provided that the Signal Screening system is on. In general these signals should be discarded.** The most distinctive feature of a normal R-wave is a relatively deep well, caused by the downward displacement of the surface as the R-wave passes the transducer. The width of this well is a good estimate of the contact time or duration of the impact, $\mathbf{t_c}$. Several examples of normal R-waves are shown in Figure X-5. The small voltage rise ahead of the sharp drop caused by the R-wave is due to the arrival of the P- and S-wavefronts, which have a higher speed than the R-wave. Note that the signal shown in (c) was generated by a shorter duration impact than the signals shown in (a) and (b).

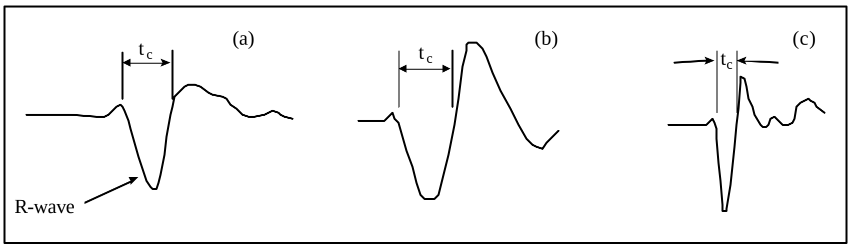


Figure X-5. Examples of normal R-waves.

Separated and irregular R-waves. For high-energy impacts the R-wave can become separated into several segments by steep vertical lines, as a result of the transducer being bounced off the surface and momentarily losing contact. In other cases, an irregular surface or crushing under the point of impact can result in an irregular shape in place of the usual rounded bottom of the R-wave well. Examples of separated R-wave are shown in Figures X-6(a) and (b) and an irregular R-wave is shown in (c). Record 15 in file **c:\ImpactDemo\TestFile.dat** exhibits a separated R-wave.

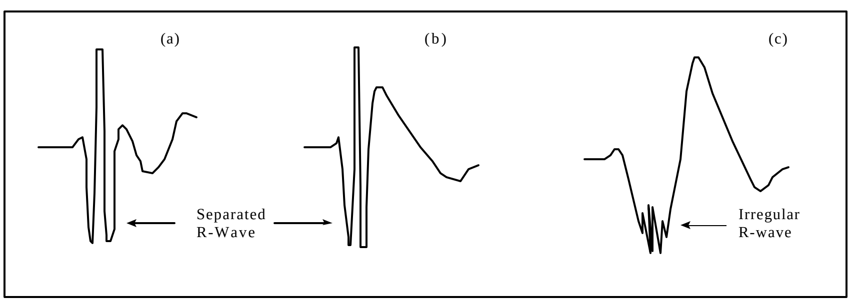


Figure X-6. Examples of abnormal R-waves: (a) and (b) separated R-wave, and (c) irregular R-wave.

The presence of a separated or irregular R-wave does not mean that the signal is invalid, but suggests that the spectrum should be examined carefully. A separated R-wave, for example, often introduces high-frequency components into the waveform that are not related to the important P-wave reflections.

Removing or “cutting” the R-wave. The problem of a separated R-wave is solved by removing it from the waveform prior to transforming the signal into the frequency domain.

1. To see an example of the distortion in the spectrum caused by a separated R-wave, start the **ImpactDemo** program and open the data file **c:\ImpactDemo\TestFile.dat**. Open record 41. The waveform and spectrum are similar to Figures X-7(a) and (b).

2. On the waveform, place the active cursor at the right side of the R-wave (at 242 μs) and click **Cut R-Wave**. The resulting changes are similar to those shown in Figures X-7(c) and (d). Removal of the R-wave removes the broad dome of high frequencies centered at about 35 kHz in (b), caused by the abnormal shape of the R-wave.

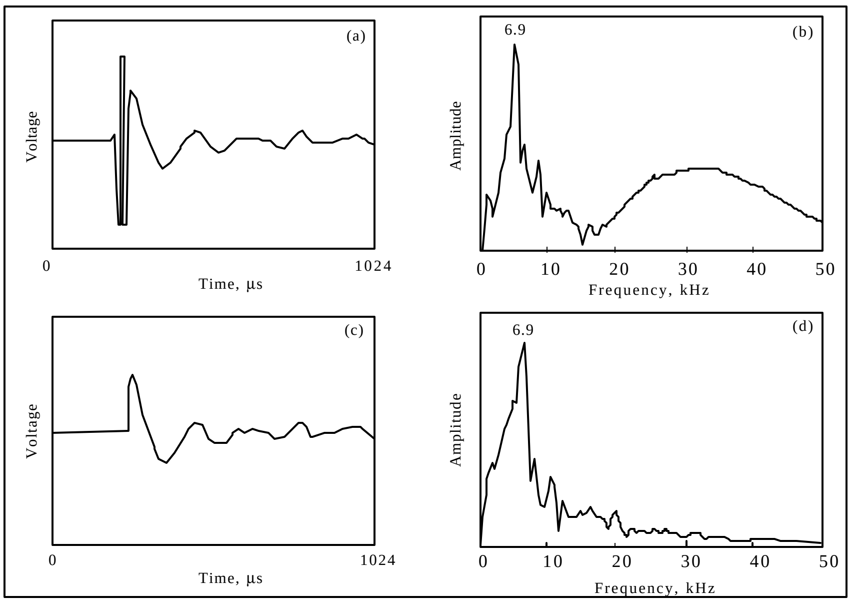


Figure X-7. Response from a test with a separated R-wave: (a) and (b), the waveform and spectrum with the R-wave included; (c) and (d), the waveform and spectrum with the R-wave removed.

It is sometimes useful to remove (cut) an R-wave that has a normal shape if its amplitude is much greater than that of the periodic signal that follows, because it can introduce frequencies that diminish or obscure the important P-wave resonances. This often occurs, for example, in tests on concrete with asphalt overlays, particularly if testing is carried out on a warm day. A waveform and spectrum from a test on a concrete bridge deck with an asphalt overlay is shown in Figures X-8(a) and (b). (In this case the large amplitude R-wave response consists of both the initial well caused by the passage of the R-wave and, immediately following, an “overshoot” response due to inertial effects in the transducer. The large amplitude R-wave has a significant effect on the spectrum. The waveform and spectrum with the R-wave removed are shown in (c) and (d). The important response, although discernible in (b), is very clear in (d). (Record 33 in the test data file, **c:\ImpactDemo\TestFile.dat**, is very similar to the test shown in Figure X-8.)

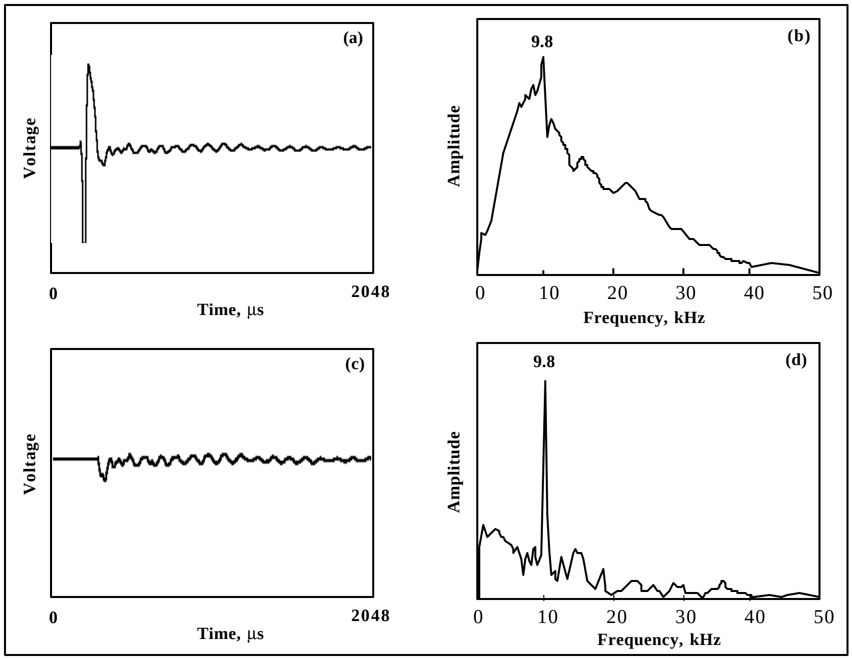


Figure X-8. An impact-echo response obtained from a concrete bridge deck with an asphalt overlay: (a) and (b) show a signal dominated by a large-amplitude R-wave; (c) and (d) show the same results with the R-wave removed.

<u>Clipping the R-wave.</u> In cases where the R-wave is dominant in every test, its contribution to the spectrum can be reduced electronically by clipping the R-wave signal. The clip level is a voltage beyond which signals are ignored, and not used in calculating the spectrum. Figure X-9 is the waveform shown in Figure X-8(a), except that the R-wave has been clipped. The effect on the spectrum is similar to that produced by cutting the waveform altogether (Figure X-7(c) and (d)) though not as dramatic. Clipping is often a convenient method for reducing the contribution of R-waves to spectra, because it can be done automatically during data acquisition, whereas removing the R-wave from the waveform must be done by the user after waveform has been plotted. Use record 33 in the test data file to observe the effects of setting different values for the clip level.

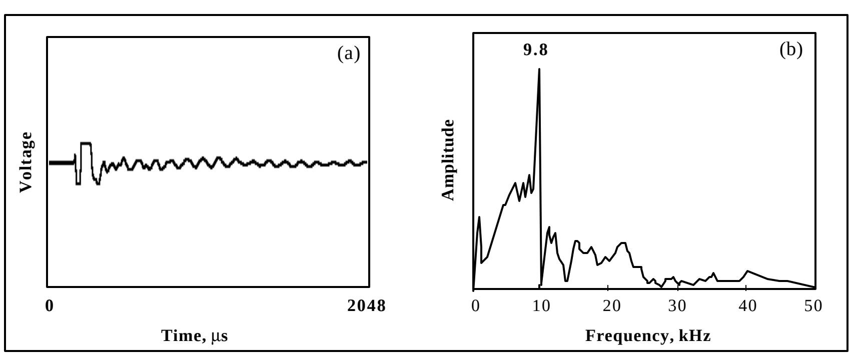


Figure X-9. The impact-echo response obtained from a concrete bridge deck with an asphalt overlay: (a) waveform with clipped R-wave, and (b) spectrum.

Interpreting the spectrum.

Spectra are valid only if waveforms are valid. Repeated tests taken in the same location with the same test set-up should produce similar patterns in spectra. If the spectrum of a test cannot be reproduced, the test is probably invalid. The following sequence of steps and questions are suggested as an approach to analyzing spectra.

(a) Examine the overall pattern in the spectrum. Is it a typical solid response for the type of structure being tested? If not, does it include a peak or set of peaks consistent with the presence of a flaw?

(b) If the fundamental solid response frequency is shifted downward, but a distinct higher frequency response is not observed, try repeating the test using a smaller impactor. This will introduce stress waves with more energy in high frequencies, which will help amplify any high-frequency response produced by a flaw at a shallow depth.

(c) If one or more frequency peaks are present, determine their frequencies and the corresponding depths. Are the depths consistent with any known or expected flaws in this structure?

(d) If a secondary peak or peaks are present, but the fundamental solid response is unchanged, check to see if the secondary peak is consistent with P-wave reflections from a concrete-steel interface, such as a reinforcing bar or tendons in a fully grouted post-tensioning duct.

(e) In situations where the R-wave has a large amplitude relative to the amplitude of displacements produced by P-wave reflections, check to see if the key features of the spectrum can be clarified by removing or clipping the R-wave in the waveform.

With experience in using the impact-echo method in a variety of applications, the above steps and questions become automatic. The response patterns obtained from different types of structures become easily recognizable.

Understanding the Effects of the Sampling Interval and Number of Samples

The choice of sampling interval and number of samples for an impact-echo test is discussed briefly on p. 18 and in more detail in Appendix **A** on data acquisition parameters. The effect of changing these numbers is illustrated with two records in the test data file.

3. Open the test data file (**c:\ImpactDemo\TestFile.dat**), and open record 43. This record shows the results of a test on a solid, 250mm thick concrete plate, with a wave speed of 3900 m/s. The plate was a laboratory test specimen, with a length and width of about 1.5 meters. The sampling interval was 2 μs (sampling rate 500 kHz) and 1024 data points were used to plot the waveform. The record length—the time period over which the signal is recorded—is the product of the number of data points, **n**, and the sampling interval, $\Delta \mathbf{t}$. In this case $\mathbf{n}\Delta\mathbf{t}$ = 1024 x 2 = 2048 μs, or about 2 milliseconds. The waveform has the general appearance of a sine wave, and the spectrum exhibits a strong "thickness frequency" peak at 7.8 kHz.

4. Click the **<u>3</u> H. Scale** text box at the lower right of the waveform, enter 2048 in place of 1024, and press the **Enter** key. The spectrum is re-plotted using 2048 data points (a record length of about 4 milliseconds). The resulting spectrum, although it still has a strong peak near 7.8 kHz, is more complicated. This is the result of the effects of wave reflections from the side boundaries of the structure, and the excitation of additional modes of vibration in a bounded structure. In this case, the addition of 2 milliseconds of time to the record length only serves to complicate the spectrum, and to make it more difficult to interpret.

5. Place the active waveform cursor at 2048 μs, and click **Cut <u>W</u>aveform**. This removes the last two milliseconds from the waveform, and recalculates the spectrum. The result is an effective record length of 2 milliseconds, and the spectrum is generally similar to that obtained in step 3 above.

6. Open record 44. This shows the results of a test at the same point as in record 43, but with a sampling interval of 4 μs instead of 2 μs. The record length is 1024 x 4 μs, or about 4 milliseconds, and the spectrum is similar to that obtained by using the same record length in step 4 above.

7. Place the active waveform cursor at 2048 ms and click **Cut <u>W</u>aveform**. The resulting spectrum, based on 512 data points at 4 ms (a record length of about 2 milliseconds), is similar to that obtained in step 5.

8. Click **Restore <u>W</u>** to restore the waveform. Click the **<u>5</u> H. Scale** text box, enter 2048 in place of 1024, and press the **Enter** key. The result is a spectrum based on a record length of 2048 x 4 μs, or about 8 milliseconds. In this case the effects of multiple wave reflections within the bounded structure have become dominant, and the thickness frequency peak at 7.8 kHz is almost lost in the noise.

9. Place the active waveform cursor at about 1000 μs and click **Cut <u>W</u>aveform**. The resulting spectrum, based on a record length of about 1 millisecond, shows a single dominant peak at 7.8 kHz. The four cycles in the waveform following the R-wave indicate that only 4 P-wave reflections were needed to obtain a clear response. Place the cursor at 2000, 3000, 4000, and 6000 ms, and cut the waveform at each of those points. The results show spectra based on record lengths of 2, 3, 4 and 6 milliseconds. It is clear in this example that increasing the record length beyond about 2 milliseconds complicates the picture.

10. Open record 41. This is from a test on a railway tunnel wall with a thickness of 300 to 400mm. The lateral dimensions were very large relative to the thickness, so that over the 4 millisecond record length there were no effects from wave reflections from the lateral boundaries. The result is a waveform that closely approximates a simple sine wave. To confirm this, place the active waveform cursor at 1000, 2000, and 3000 μs, and cut the waveform at each of those points. The resulting spectra are remarkably similar. Place the active cursor at any point on the waveform and click **Cut <u>R</u>-Wave**. Place the cursor at a point at least 800 μs to the right of the first point and click **Cut <u>W</u>aveform**. The resulting spectrum shows the frequency content of the waveform between those two points. It always

displays a dominant peak at about 6.3 kHz, confirming that a single frequency dominates the entire waveform.

Appendix A: Setting The Data Acquisition Parameters

Data acquisition parameters are parameters that define the conditions under which the analog signal from the hand-held transducer unit is digitized for transfer to the computer memory. For routine testing the data acquisition parameters are set automatically by the software. However, it is possible to override the default values by accessing the **Parameters for Data Acquisition** screen, shown in Figure A-1. This screen is accessed from the **Main Menu** screen.

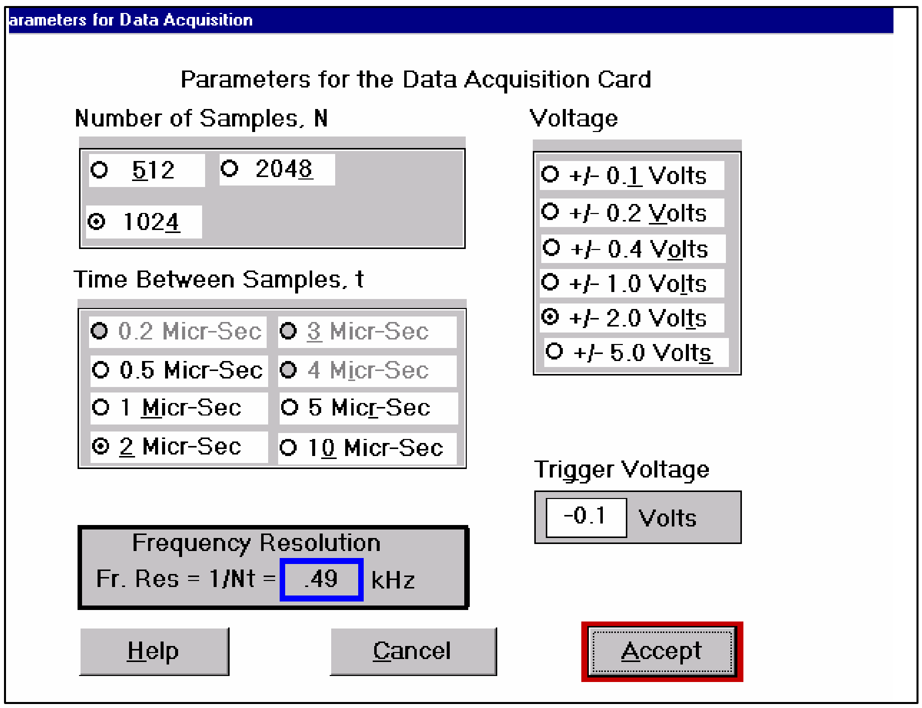


Figure A-1. The **Parameters for Data Acquisition** screen.

The parameters that can be selected or changed on this screen, and their role in the analog-to-digital signal conversion process, are the following:

<u>Number of Samples</u>. When a test is performed, the system *always* records 2048 data points (voltages), separated by the time interval specified under **Time Between Samples**. Because these voltages are proportional to displacement, a plot of voltage vs. time is called a displacement/time curve or waveform. The **Number of Samples** entered on this screen is the number used by the computer to plot the waveform and to calculate the amplitude spectrum. Specifying the number of samples as a power of 2 (i.e., 512, 1024, 2048) makes the most efficient use of the mathematical algorithm (called fast Fourier transform, or FFT) used to calculate the amplitude spectrum from the waveform. The default value for this parameter is 1024, a value suitable for most testing. The effect of using different numbers of samples to calculate the

spectrum can be explored by changing the horizontal scale for the waveform when a record is displayed.

Time Between Samples. An important aspect of impact-echo testing is the reliance on short sampling periods to limit the response to P-wave reflections from the region directly beneath the impact point. The sampling interval, D**t**, must be sufficiently short to resolve the highest frequencies of interest. At the same time the record length, ***nDt*** (where ***n*** is the number of samples), must be sufficiently long to identify the important frequencies in the response and to provide a reasonable level of frequency resolution, but short enough to avoid multiple reflections from the side boundaries of the structure. It often appears desirable to maximize the frequency resolution by setting ***n*** to the maximum level of 2048, and *D**t*** to 4 µs or higher. Although this provides a frequency resolution four times better than the recommended starting values of 1024 for ***n*** and 2 µs for *D**t***, a very real risk exists that, unless the test is being performed on a thick structure or a very large plate, a record length of 8192 micro-seconds (2048 x 4) will allow multiple reflections of both R- and P-waves from the side boundaries to become part of the waveform, adding frequency peaks that complicate the response. A time interval between samples of 1 microsecond is equivalent to a sampling rate of 1 MegaHertz (MHz) or one million cycles per second. The minimum time interval is 0.5 micro-seconds, equivalent to a sampling rate of 2 MHz. The default value set by the Impact-E software for impact-echo testing is 2 microseconds, a value suitable for most testing. For wave speed measurements, the time between samples is automatically set to 0.5 microseconds, and the system samples simultaneously on two channels.

Frequency Resolution. When the waveform is processed by means of a fast Fourier transform (FFT) the result is a table of amplitude vs. frequency, called an amplitude spectrum (*Sansalone and Streett*, Chapter 5). The points in this spectrum are calculated for a fixed number of discrete frequencies. Frequency resolution is the frequency difference between successive points in the calculated spectrum. If ***n*** is the number of samples in the waveform and *D**t*** is the time between samples, the spectrum calculated by the FFT will contain ***n*/2** points and the frequency interval between them—the frequency resolution—will be 1/***nDt***. The frequency resolution is displayed on the **Parameters for Data Acquisition** screen, and also on the screen with the results of a test, where it appears in the upper right corner of the spectrum graph. (See, for example, Figure IX-2.) At first glance it might appear desirable to improve (decrease) the frequency resolution by increasing ***n*** or *D**t***; however, it can be misleading to consider the expression 1/***nDt*** in isolation. For routine testing of plates, beams, columns, and other common structures, sampling intervals of 1 to 4 microseconds and sample numbers of 1024 to 2048 are recommended. The resulting frequency resolutions range from 0.12 to 0.98 kHz. For more information about choosing ***n*** and *D**t*** for specific applications, and about the effect of frequency resolution on the precision of depth and thickness measurements in impact-echo tests, see Chapter 6, "Digital Signals" in *Sansalone and Streett*.

Voltage. The data acquisition system is bipolar, which means that it responds to both positive and negative voltages. The possible settings for the voltage range from $\pm$ 0.1 to $\pm$ 5.0 volts. With current technology, each data point is recorded as a 14-bit number. It follows that the voltage resolution (the uncertainty introduced by the digitizing process) is $V/(2^{14})$, or one part in 16384 of the absolute value of *V*. For the ranges $\pm$0.5, $\pm$2.0, and $\pm$5 volts, for example, the uncertainties in the voltage are 0.00003, 0.0001, and 0.0003 volts, respectively, or 0.006% of the maximum

voltage. In normal impact-echo testing it is rare for the output signal from the transducer to exceed 2 volts; therefore, a voltage range of $\pm$2.0 volts is the default value automatically set by the software. The waveform for an impact-echo test on a 250mm thick concrete plate, with the voltage range set at $\pm$2.5 volts, is shown in Figure A-2. The zero point in voltage is at the center of the vertical axis, and the extremes of + 2.5 and - 2.5 volts are at the top and bottom.

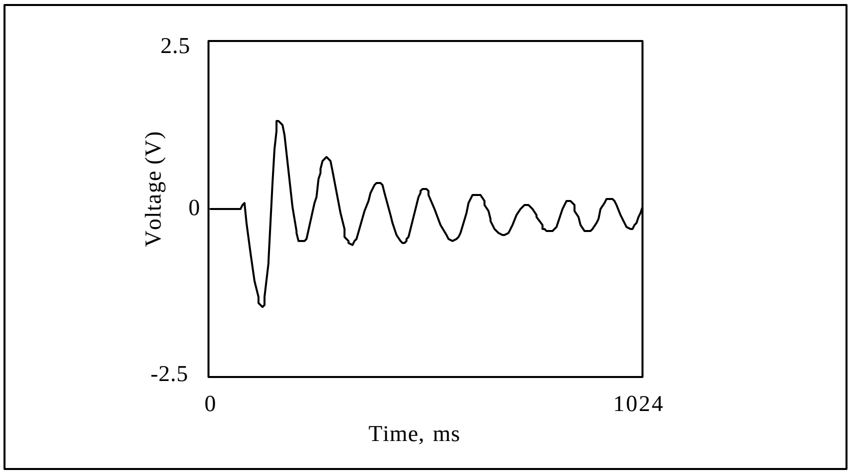


Figure A-2. Waveform from impact-echo test on a solid plate, 250mm thick.

In this example, the maximum voltage in the waveform is about 1.5 volts, and the uncertainty is 0.0001volts, or about 0.007 percent. The maximum voltage in impact-echo signals is usually less than 2 volts, and often less than 1 volt, so these values are suitable for routine testing.

The voltage setting, ***V***, appears at the lower left of the waveform graph when the results of a test are displayed on the computer screen. If the vertical scale on the waveform graph is set to the same value as the voltage, and the waveform remains within the graph when a test is performed, the output of the transducer is within the selected voltage range, and ***V*** need not be changed. If the waveform is cut off at the top and bottom of the graph, the transducer output exceeds the selected voltage setting, and ***V*** should be increased. A voltage setting of $\pm$ 2.0 volts is satisfactory for most testing of plates, beams, columns and other common structures. Higher voltage settings can be used if the signals are very strong, and lower voltage settings can be used if the signals are especially weak.

For wave speed and crack depth measurements, where the highest resolution is needed, a default value of 0.1 volts is used. Values of 0.2 or 0.1 volts are recommended for these tests.

Trigger Voltage. This parameter instructs the data acquisition system to “trigger”, or save a set of digitized data points, when the analog voltage from the transducer unit reaches this value and the slope of the voltage time curve is negative (the voltage is decreasing). The significance of the **Trigger Voltage** parameter is illustrated in Figure A-3, which shows the leading part of a typical waveform.

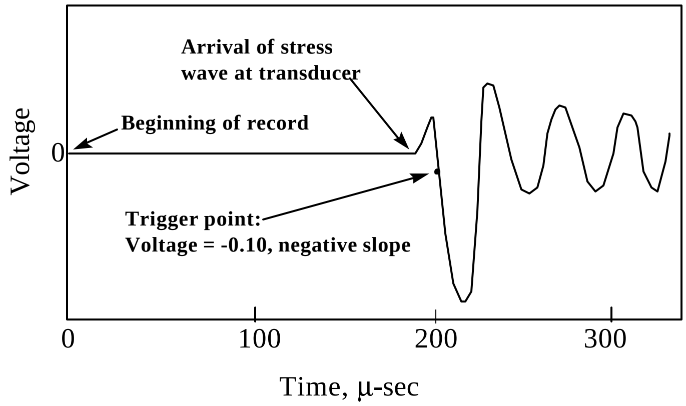


Figure A-3. Leading portion of waveform, illustrating the significance of the trigger voltage.

When the data acquisition system is activated by the computer, it begins recording continuously into its on-board memory, reading data points (digitized voltages from the transducer) into one end of a buffer and pushing them out the other end. Prior to the impact there is no signal from the transducer (input signal is zero) and a string of zeros is fed into the buffer. When the stress waves arrive at the transducer, a voltage is generated, and the early part of the signal is used to initiate or "trigger" the data acquisition process. The **Trigger Voltage** instructs the system to begin recording data points when the input signal reaches a set value (typically -0.05 to -0.25 volts), and the slope of the voltage/time curve is negative (voltage decreasing with time). This insures that triggering occurs just after the arrival of the R-wave, which produces a sharp drop in voltage. If there are mechanical vibrations in the structure being tested, they will sometimes trigger the system before or after the impact. If this occurs, the **Trigger Voltage** should be assigned a value in the range -0.15 to -0.25. The data acquisition system is set to record approximately 196 data points prior to the trigger point. This insures that the earliest wave arrival at the transducer is part of the data stream transferred to the computer.

Clip Level. Clip level specifies a voltage beyond which signals are cut off and ignored. It is used primarily to cut or "clip" very large R-waves that would otherwise dominate the signal and obscure other features. Examples of the use of the clip level are given in Section VII of this manual. For a more detailed discussion of the use of clip level, including examples, see pages 314-15 in *Sansalone and Streett*.

Cancel and Accept Buttons. Activating either of these buttons returns control to the **Main Menu** screen. If changes have been made in the data acquisition parameters, they are not saved if the **Cancel** button is activated.

Appendix B: ASTM Standard C-1383-98a Measuring P-Wave Speed and Plate Thickness Using the Impact-Echo Method

Index